

**A Framework for Evaluating Advanced Search Concepts for  
Multiple Autonomous Underwater Vehicle (AUV) Mine  
Countermeasures (MCM)**

by

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B.S., Ocean Engineering,  
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Submitted to the Department of Ocean Engineering  
in partial fulfillment of the requirements for the degrees of

Naval Engineer

and

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## **Abstract**

Waterborne mines pose an asymmetric threat to naval forces. Their presence, whether actual or perceived, creates a low-cost yet very powerful deterrent that is notoriously dangerous and time-consuming to counter. In recent years, autonomous underwater vehicles (AUV) have emerged as a viable technology for conducting underwater search, survey, and clearance operations in support of the mine countermeasures (MCM) mission. With continued advances in core technologies such as sensing, navigation, and communication, future AUV MCM operations are likely to involve many vehicles working together to enhance overall capability. Given the almost endless number of design and configuration possibilities for multiple-AUV MCM systems, it is important to understand the cost-benefit trade-offs associated with these systems.

This thesis develops an analytical framework for evaluating advanced AUV MCM system concepts. The methodology is based on an existing approach for naval ship design. For the MCM application, distinct performance and effectiveness metrics are used to describe a series of AUV systems in terms of physical/performance characteristics and then to translate those characteristics into numeric values reflecting the mission-effectiveness of each system. The mission effectiveness parameters are organized into a hierarchy and weighted, using Analytical Hierarchy Process (AHP) techniques, according to the warfighter's preferences for a given operational scenario. Utility functions and modeling provide means of relating the effectiveness metrics to the system-level performance parameters. Implementation of this approach involves two computer-based models: a system model and an effectiveness model, which collectively perform the tasks just described. The evaluation framework is demonstrated using two simple case studies involving notional AUV MCM systems. The thesis conclusion discusses applications and future development potential for the evaluation model.

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To my wife, Stacey, and daughter, Alyssa.  
For your unfailing love and support, and the many sacrifices that you make on my behalf,  
I thank you.

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# Chapter 1

## Introduction

### 1.1 Motivation

#### 1.1.1 The Role of AUV MCM Systems in Naval Operations

Autonomous underwater vehicles (AUV) are recognized by the U.S. Navy as a vital technology for future battlespace preparation and tactical operations in support of a broad range of warfare missions [1]. Among these missions is mine countermeasures (MCM), which generally consists of two sub-missions: mine reconnaissance and mine clearance. The MCM “mission need” is difficult to bound since it is tied directly to the larger warfighting requirements of sea control and access. In the near-term, the Navy is focused on conducting rapid, in-stride reconnaissance operations in the littoral region to enable fast-paced expeditionary operations [2], [3]. Achieving this level of capability represents a significant leap from that of today’s MCM force. The true MCM mission need goes far beyond in-stride reconnaissance to include such challenging operational scenarios as covert surveillance, detailed bottom mapping, and mine clearance – all required to be done quickly, over large areas, and from deep water to the shoreline. AUV systems have the inherent characteristics to satisfy this MCM mission need. Increasingly capable and relatively inexpensive, these systems could offer the naval commander unprecedented leverage and flexibility in conducting rapid, yet thorough, underwater search and clearance missions with minimal risk to human life.

Within the U.S. defense community, many underwater vehicle system development efforts

are presently underway, several of which are intended for the MCM mission. The Remote Mine-hunting System (RMS) is an unmanned system composed of a semi-submersible vehicle and a towed body collectively housing an array of sonars. It is to be back-fit onboard DDG 51 class destroyers, beginning in 2004, to provide an “organic” mine reconnaissance capability to the fleet. While not truly an AUV, it represents an incremental step toward in-stride, unmanned MCM. Also by 2004, the Navy plans to introduce its first tactical unmanned undersea vehicle (UUV)<sup>1</sup>, the Long-term Mine Reconnaissance System (LMRS) – a submarine-hosted vehicle with the planned capability to conduct clandestine mine reconnaissance. The Office of Naval Research (ONR) is funding other underwater vehicle research and development efforts, including a small modified oceanographic AUV called SAHRV, or Semi-autonomous Hydrographic Reconnaissance Vehicle, for minehunting in very shallow water regions[6]. Even while these pioneering programs are being implemented during this decade, continuing advances in AUV technology areas coupled with expanding confidence in AUV performance should enable steady progress toward more unconventional unmanned MCM systems. In their 1997 report [5], the National Research Council Committee on Technology for Future Naval Forces predicted the availability of “highly autonomous UUVs that operate in cooperative engagements” and are “capable of sensing their environments and communicating with each other to optimize underwater missions” in the 2035 timeframe. Relative to today’s capability, or even the near-term capability goals, the advent of these “cooperative multiple-AUV systems” will lead to vastly superior MCM systems.

### **1.1.2 Transition to Cooperative Multiple-AUV Operations**

Cooperative multiple-AUV systems will strive to enhance overall system effectiveness by leveraging the individual capabilities of vehicles comprising that system. These individual capabilities can be stated in terms of vehicle sub-components, e.g. sensors, navigation units, data storage and processing devices, communications gear, and payload items. Functionally linking these physically distributed sub-components is *communication*, the bedrock capability of a multiple-vehicle system. Without intra-system communication, the benefits of employing multiple assets

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<sup>1</sup>The U.S. Navy often uses the term UUV when referring to unmanned underwater vehicle systems. An AUV is a type of UUV.

are reduced to the trivial case of cloning vehicles to reduce mission time. With communication, however, multiple-platform paradigms offer opportunities far beyond the simple linear scaling of performance. Such opportunities include multiple-sensor data fusion, collaborative navigation and localization, communications relay, and optimal asset allocation. The presence of multiple vehicles within a system, taken together with the probable communication link between the system and a host (e.g. a ship, submarine, satellite, etc.), also impacts the guidance and control architecture and underlying algorithms required for the system to function properly.

The challenges of implementing AUV MCM systems, cooperative multi-AUV systems aside, are both technological and operational in nature. Beside the physical issues – energy source and through-water communication being two of the most daunting – there are significant operational control and oversight concerns that must be addressed. Engineers, systems integrators, and operators will have to sort through and understand these issues in seeking proper balance between overall system effectiveness and the cost required to achieve it.

## 1.2 Problem Statement

In the last decade, underwater vehicle research has led to great advances in such technologies as sensing, navigation, guidance, control, and communication. To reap the full potential of these technologies, AUVs must be capable of working together in a cooperative manner, making the best use of their complementary capabilities. Such systems may be composed from a vast range of vehicle types and sizes, sensors, navigation suites, communication packages, etc., resulting in a nearly limitless set of alternative configurations. For this reason, the design and employment of a cost-effective multiple-AUV system requires an understanding of the system's dynamics and, in particular, the relationships between system configuration and performance characteristics. Typical questions that may be posed by decision-makers are:

1. What is the right combination of AUV assets to employ for a particular mission? Should we use many inexpensive vehicles, a few high-performance vehicles, or a combination of the two?
2. What types of sensors and how many of each are required for a particular mission? What are the sizes of the vehicles that must carry these sensors?

3. What navigation requirements are imposed and what navigational opportunities are created by multiple vehicles?
4. What are the communication requirements between the vehicles and/or the Navy host platform?

These are important and difficult questions, and they must be answered. Ultimately, though, it is the overall system effectiveness – the degree to which the system serves its intended purpose – that must be assessed in order to make appropriate decisions and therefore resolve these issues.

### 1.3 Objectives

The overarching objective of this thesis is *to develop an analytical framework for the evaluation of advanced search concepts for multiple-AUV MCM*.

The effort described herein contributes to a larger project, funded by ONR, that aims to identify and evaluate a range of multiple-AUV operational paradigms for MCM missions [8]. This project, referred to as the “ONR project”, is described briefly in Section 2.1. In the early stages of the ONR project, the author and other participants identified the need for two basic levels of the eventual framework that would be used to evaluate notional AUV systems. The upper level would provide an environment for rapidly exploring various multi-AUV system configurations and tactical approaches for a given MCM scenario. The lower level would predict system performance and behavior in each case, perhaps through high-fidelity simulation, and provide the results to the upper level. The thesis focuses on the development of, methodology behind, and application for the overall evaluation framework.

The intended thesis “product” is a computer-based decision-making tool. At the outset of the work, two core applications were identified for use in guiding and determining the scope of the project. These applications are presented in the form of the following questions:

1. What AUV MCM system, in terms of individual vehicle design(s) and/or multi-vehicle combinations, most affordably meets the mission need and requirements?
2. What is the most effective system configuration and operating profile for an AUV system embarked on a particular mission?

The first question relates to design and acquisition, while the second has more to do with operational employment. Realistically, a decision-maker will never possess the knowledge required to answer these questions definitively. He can only hope to obtain the “best” solution by exploring the cost-effectiveness of each alternative according to his decision-making criteria.

In support of the overall thesis objective, the following enabling objectives were set:

1. Identify performance parameters and measures of effectiveness for multi-vehicle MCM approaches.
2. Identify and select advanced multi-AUV sensing and navigation schemes which have potential for minehunting application.
3. Create a computer-based multiple-AUV performance assessment model.
4. Develop a cost-effectiveness model that facilitates translation of system performance characteristics into effectiveness scores and cost values.
5. Evaluate the cost-effectiveness of notional multiple-AUV systems.

## **1.4 Outline**

The thesis is organized into five chapters and three appendices. Chapter 2 briefly discusses other research efforts related to the use of underwater vehicles for MCM. Chapter 3 is the heart of the thesis. It details the methodology behind and the development of the evaluation framework. In Chapter 4, two case demonstrations are presented to illustrate the evaluation approach. A summary of the thesis and a short discussion of applications and possible follow-on work are given by Chapter 5. The appendices contain printouts of the Evaluation Model developed in the thesis.



## Chapter 2

# Related Research

### 2.1 Overview

During the course of this thesis, the author became aware of a several major MCM systems research efforts being conducted by members/associates of the MCM community. In general, these fall into two broad application categories: very shallow water and surf zone (VSW/SZ), shallow water and deeper (SW). ONR currently funds a large number of individual and group projects that contribute to these efforts. Some of the organizations undertaking or involved in these projects include:

Coastal Systems Station (CSS), Dahlgren Division, Naval Surface Warfare  
Center (NSWC); Panama City, Florida  
Naval Undersea Warfare Center (NUWC); Newport, Rhode Island  
Massachusetts Institute of Technology (MIT)  
Johns Hopkins University (JHU), Applied Physics Laboratory (APL)  
Applied Research Laboratory (ARL), University of Texas (UT) at Austin

Brief descriptions of those research efforts most applicable to this thesis are provided in the following sections. To at least some degree, the author collaborated with members from each of these organizations during the course of the thesis.

## 2.2 MIT Ocean Engineering Department

As previously stated, the thesis contributes to a joint MIT Sea Grant - Bluefin Robotics Corporation project, funded by ONR, titled *Sensor and Operational Trade-offs for Multiple AUV MCM*. The objective of the project is “to develop the tools necessary to create a simulation environment in which to conduct sensor and platform trade-off studies for MCM missions involving multiple AUVs”. As proposed, the work will lead to an advanced multi-vehicle simulation capability using high-fidelity physics-based models.

While working on this thesis, the author communicated regularly with other members of the ONR project team. The framework developed herein will be used to guide the continued multi-AUV simulation and modeling effort.

In addition to the ONR project, several ongoing research efforts within the MIT Ocean Engineering Department are applicable to the AUV concepts and technologies motivating this thesis. The research, mostly Navy-funded, can be categorized under the fields of ocean acoustics and underwater vehicle navigation.

Professor Henrik Schmidt, who is the Principal Investigator for the ONR project and the advisor for this thesis, is currently engaged in a project examining new sonar concepts for shallow-water MCM. The project, called GOATS<sup>2</sup>, involves expanding a previously developed multi-AUV concept known as Autonomous Oceanographic Sampling Network (AOSN) [10]. During GOATS experiments in 1998 and 2000, participants explored the use of multiple, mobile platforms for mono-, bi-, and multi-static sensing and 3-D mapping of bottom objects, including buried mines [9]. These experiments have revealed the potential benefits of using multiple, distributed AUVs to cooperatively conduct MCM searches in the VSW region of the littoral. An expected by-product of this work is the capability to acoustically model advanced multi-AUV sensing concepts. Such models will hopefully predict system-level detection/classification/identification probabilities of notional multi-sensor configurations, and would nicely complement the evaluation framework developed in this thesis.

The ability to conduct clandestine MCM operations will require AUV systems to navigate with high accuracy, ideally without having to penetrate the surface at all. Professor John

---

<sup>2</sup>Generic Oceanographic Array Technology System

Leonard's research is concentrated in the area of advanced navigation and mapping technologies for underwater vehicles. In recent years, a main thrust has been feature-based concurrent mapping and localization (CML), a technique which enables an AUV to build a map of an unknown environment while simultaneously using that map to navigate with bounded position error [11]. The feature-based CML approach relies on high-resolution sonar data from which compact features, such as mines, lobster-traps, rock outcroppings, and so forth can be extracted. These features are then used to build the map that the AUV can use to determine its position and navigate from over an extended period of hours or days. This research is sponsored by NUWC.

## **2.3 MCM Future Systems Working Group**

JHU/APL, ARL:UT, and CSS Panama City constitute the core of the MCM Future Systems Working Group. MIT and several other organizations are designated as supporting members of this working group. Since January 1998, the group has developed an array of system concepts, identified/researched future technologies, established performance metrics, and conducted a significant amount of analysis, mostly geared toward underwater vehicle systems for the SW MCM problem. Models developed include a UUV endurance model and associated cost model, and a MATLAB-based model for MCM-related calculations for UUVs. These models have been used to assess the MCM efforts of multiple underwater vehicles, but they are not intended for cooperative multi-vehicle systems. The evaluation framework developed in this thesis leverages some of the research provided by the working group, and is intended to complement their efforts.

## **2.4 Naval Warfare Centers**

CSS and NUWC are two Navy warfare centers possessing a great deal of capability for UUV research and engineering. Additionally, CSS is very involved in a broad range of MCM systems engineering and analysis, with programs for surface-, air-, and underwater-based MCM. At CSS, work is being done in support of both the VSW/SZ and SW problems. Most applicable to this thesis are high-level simulation/evaluation analyses being performed for UUVs in the VSW/SZ problem, and separately for comparing unmanned surface vehicles (USV) MCM system concepts

to UUV concepts. NUWC has, in the past, been aligned with the anti-submarine warfare community and had little opportunity to participate in MCM system R&D work. However, the introduction of LMRS and other potential submarine-based and/or undersea warfare UUVs has caused NUWC to become involved in MCM system development. NUWC is also tasked with drafting and managing the Navy's UUV Master Plan – a visionary document establishing the broad missions and required capabilities for all Navy UUVs [1].

## Chapter 3

# Evaluation Framework

The objective of this thesis is to develop a framework for the evaluation of advanced search concepts for multi-AUV MCM. Chapter 3 addresses the development and architecture of this framework.

### 3.1 Approach

In the general context of warfare systems, determining the “right” system for a particular mission need is a complex and challenging endeavor. From the early design phase to operational implementation, the process of fielding a typical warfare system involves many parties, each of whom make decisions according to a different set of criteria. A designer tends to focus on specific, intrinsic system characteristics (e.g. size, speed, and efficiency) that allow optimization of the system from an engineering standpoint, while the end user is concerned about the extent to which the system satisfies their own set of preferences or objectives. Additional parties may also impose objectives or constraints of their own, such as cost or production schedule. Evaluating the overall cost-effectiveness of a system is further complicated when the system’s role in a larger “system of systems” is considered. For warfare system design and implementation, these realities demand a decision-making framework which integrates the contributions and preferences of all parties and measures the system’s effectiveness at the highest practical level of the system of systems hierarchy.

An integrated design decision-making approach is used to varying degrees within the U.S.

Navy for system design and acquisition. Navy program offices and their supporting warfare and analysis centers evaluate system alternatives through a process called Analysis of Alternatives (AOA), which formalizes the procedure for assessing and documenting trade-offs associated with major program decisions [12]. In the AOA process, the “value” of a particular system alternative is established using parameters called measures of effectiveness (MOE) and measures of performance (MOP). The manner in which these MOE and MOP are identified and evaluated to support decision-making, however, is not rigidly established and so their use varies widely. In recent years, naval ship design curriculums at both Naval Post-graduate School (NPS) and Massachusetts Institute of Technology (MIT) have adopted “total ship system engineering” approaches to naval ship design. These approaches generally employ mission-oriented MOE and system-oriented MOP, prioritized via a system hierarchy, to evaluate the cost-effectiveness of several ship or submarine design alternatives with respect to the mission requirements.

As a first step toward defining a multi-AUV MCM system evaluation framework, it is useful to compare the circumstances surrounding the evaluation of a multi-AUV MCM system versus a naval ship. The basic objective for each is the same: to identify the most cost-effective solution as measured against the collective set of criteria established by all parties involved in the process. Additionally, in each case, the set of effectiveness criteria is derived from a warfare mission to which other systems or platforms are also making a contribution. There are several striking differences between the two cases, however. One is found by considering their physical layouts. The ship is a single unit, while the multi-AUV system is, of course, a collection of individual vehicles. Adding to this contrast, the vehicle composition of a multi-AUV system could vary, even within a given mission scenario<sup>3</sup>. Beyond the physical differences lie unique operational and system dynamics issues associated the “virtually connected” and “artificially intelligent” multi-AUV system. Based on these characteristics, a multi-AUV system could be considered, from an evaluation standpoint, analogous to the networked task force or battle group directly above the naval ship in the system hierarchy. Interestingly, the AUV system is itself part of that same task force (since its purpose is to conduct MCM operations on behalf of the other members of that force). A framework for evaluating multi-AUV systems must, therefore, be

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<sup>3</sup>This statement presumes that future AUV systems will consist of re-configurable and operationally flexible platforms that facilitate low-cost “mixing and matching” of not only vehicle sub-systems, but vehicle types within the system as well.

structured to handle the determination of effectiveness on several system hierarchy levels.

The evaluation framework proposed in this thesis is based primarily on an approach presented by Hockberger [13] for naval ship design. Hockberger combines several well-known systems engineering practices and decision-making methods in a framework suitable for naval ship design, emphasizing the importance of determining the ship's effectiveness in the context of its "supersystem". The proposed framework also incorporates techniques used by Whitcomb [14]. Whitcomb's approach, which is itself based partly on the work of Hockberger, uses multiple-criteria decision-making (MCDM) methods to integrate multiple customer and company preferences into the product design optimization process. The multi-AUV MCM system evaluation framework presented here provides an environment in which various system concepts, as defined by a system designer, can be evaluated in terms of overall cost-effectiveness from the perspective of the warfighter.

### 3.2 Framework Architecture and Components

The evaluation framework consists of two main components: an *effectiveness model* and a *system model*. A third component – the cost model – is required to complete the framework. For this thesis, cost estimates for AUV MCM systems are obtained using an underwater vehicle cost model developed for the MCM Future Systems Study discussed in Section 2.3. The effectiveness and system models are analytical in nature, meaning they use mathematical relationships to describe the system. As with any modeling effort, maintaining a balance between robustness, validity, programming effort, and flexibility required careful planning and structuring of the model environment. In this case, the general approach was to make the higher levels of the model as generic as possible, and to increase detail and resolution with each progression into the lower levels. This was accomplished by developing separate model sub-components and linking them together to form the overall system model, thereby achieving robustness without losing flexibility. Figure 3-1 illustrates the relationship between the framework components as envisioned early in the development process.

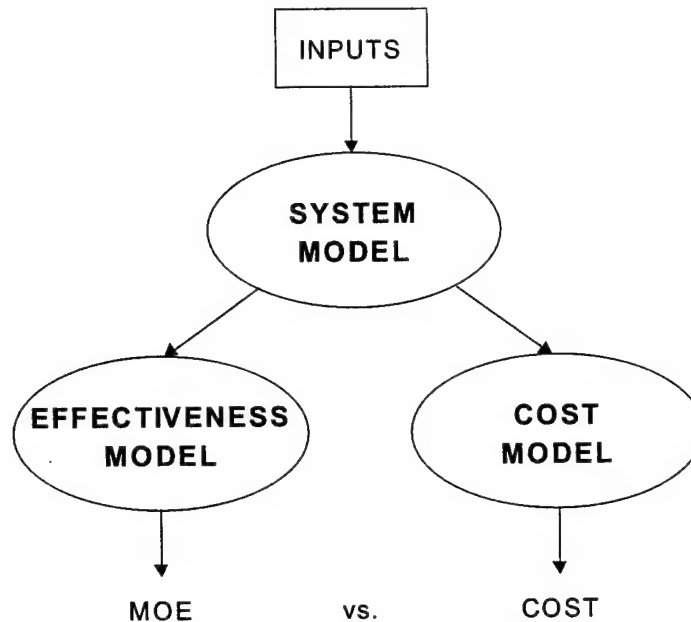


Figure 3-1: Evaluation Framework Model Components

### 3.2.1 Effectiveness Model Component

The effectiveness model addresses the objectives of the warfighter. These objectives are based on the mission, and are completely external to the system employed to pursue them. At the same time, it is essential that the objectives selected to represent the mission are a “complete, consistent, and correct” set of objectives with respect to the system(s) being evaluated [13]. An appropriate set of objectives can be selected and organized using common problem-solving and decision-making techniques, such as Quality Function Deployment (QFD) [16] and the Analytical Hierarchy Process (AHP) [17]. AHP is also an excellent tool for generating the priorities, or relative weights, of the objectives at each level in the effectiveness model in order to capture which aspects of the mission are most important to the warfighter. Another key aspect of the effectiveness model is the use of MOE. MOE measure the extent to which a system achieves the warfighter’s objectives. They can be given in terms of real units (e.g. knots) or as a scaled or normalized numerical score (e.g. 0.75 on a scale of 0 to 1). MOE values are necessarily dependent on system characteristics through sometimes difficult-to-establish relationships (discussed later). When properly selected, organized, weighted, and informed, the



MOE set provides a concise structure for presenting the effectiveness of a system alternative.

### **3.2.2 System Model Component**

The system model plays two complementary roles in the evaluation framework. First, it provides a design environment in which the “user” defines a multi-AUV system in terms of its basic sub-components (e.g. sensors, navigation packages) and their associated performance characteristics and then “balances” that system to satisfy certain design requirements and constraints. Like most engineering models, the system model employs mathematical relationships to describe the interaction between the system’s components and to ensure compliance with the basic laws of physics. By working through the system design process and observing the effects on system performance/effectiveness, the designer gains at least a partial understanding of the system’s functional behavior. The second role of the system model is to estimate the physical and performance characteristics of a multi-AUV system. These characteristics are presented as MOP<sup>1</sup>, which are then used as inputs to the effectiveness model.

### **3.2.3 Integration of the Model Components**

The effectiveness and system models can be viewed as agents working on behalf of the key players involved in multi-AUV MCM system implementation. The effectiveness model represents the warfighter, whose objectives are tied to mission scenarios which demand some level of MCM effort. The system model represents the designer or engineer, whose task is to optimize the system within the bounds of some set of requirements and constraints. The role of the agents is to establish a link between the efforts of the designer and the objectives of the warfighter so that, in effect, the designer’s frame of reference for optimization of the system is expanded to be the warfighter’s objectives. By doing so, a conceptual multi-AUV MCM system configuration can be evaluated in terms of its ability to satisfy the mission requirements rather than specific performance requirements that mean little to the warfighter.

Of course, other players may be involved in the process, and their interests must be represented as well. Such interests may include manufacturing capabilities, technology limitations,

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<sup>1</sup>The distinction between MOE and MOP is critical to understanding the framework developed in this thesis and, beyond that, for all applications that use these parameters. In short, MOE are tied to the mission (alternatively: the customer’s requirements) while MOP are properties of the system (or product).

and cost. Often, these interests are addressed through constraints imposed directly on the designer. Cost, however, generally warrants independent consideration for several reasons. First, cost is somewhat unique in that several parties may have a vested interest in it, depending on the type of cost considered and the context of the evaluation. Acquisition cost is usually linked to annual defense budget constraints, as mandated by Congress, while the impact of life cost (e.g. operations, support, maintenance) concerns decision-makers at many levels, from Congress who allocates the money, to the warfighter who must carefully manage their fiscal resources. Second, cost constraints are difficult to establish. Decision-makers would prefer to get the “most for their money” rather than draw the line at some arbitrary upper cost limit. Given these unique characteristics, cost is best treated as a separate parameter against which the mission-effectiveness of the system can be compared.

The effectiveness model and system model are linked by defining either qualitative or quantitative relationships between the MOP of the system model and the MOE of the effectiveness model. Since MOE require input from one or more MOP, an MOE is said to be a function of MOP. Techniques for establishing the MOE-MOP relationships include modeling/simulation and direct assessment [13], [14]. Modeling and simulation efforts require a significant initial time investment and can be restrictive. However, if implemented properly, they permit rapid evaluation of complex problems and may be used repeatedly for similar applications. Direct assessment involves a dialog between the evaluator and decision-maker. Based on the results of the evaluator/decision-maker interaction, the evaluator constructs a utility function which reflects the judgement, preference, and/or experience of the decision-maker. Since each technique has certain strengths and weaknesses, many evaluations use both techniques either for separate aspects or to augment one another.

### **3.3 The Overall Evaluation Process**

Whether for design- or employment-related decisions, a formal evaluation process is needed to properly and consistently assess multi-AUV system(s) cost-effectiveness. This process involves three basic phases: *problem definition*, *generation of solution alternatives*, and *modeling/evaluation of alternatives*. The problem definition phase is associated with the effectiveness

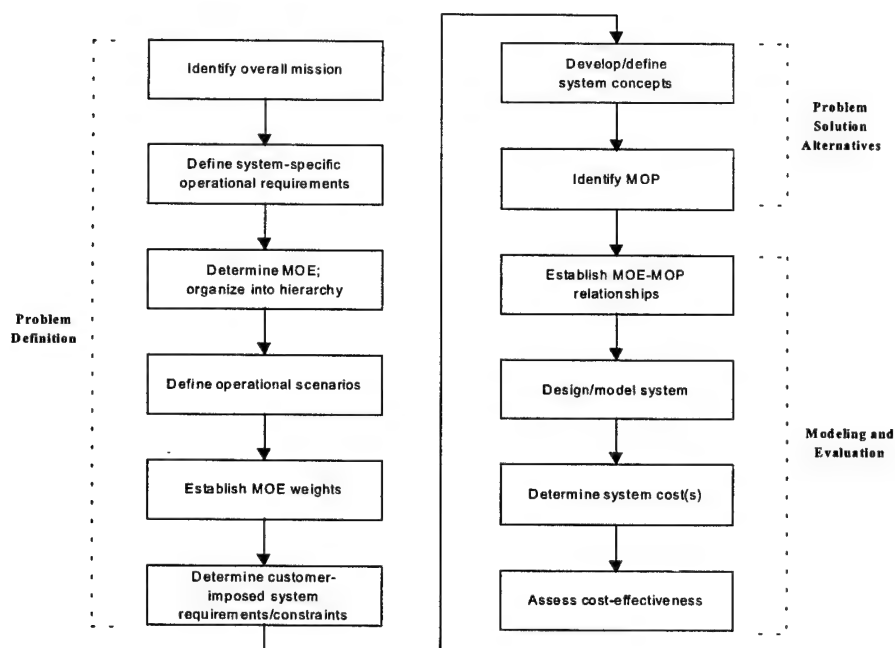


Figure 3-2: Evaluation Process Flowchart

model. During this phase, the overall mission is defined and the appropriate MOE hierarchy established. Next, operational scenario(s) are defined which characterize the environment and mine threat. Based on the mission and the operational scenario(s), MOE weights must be determined. These weights should reflect the warfighter's opinions regarding the relative importance of each MOE. (A method for determining these weights is discussed in Section 3.4.4)

Once the mission aspects are addressed and the effectiveness model is set up, the assessor develops alternative solutions to be evaluated, along with corresponding MOP. If not already known, the MOE-MOP relationships must be derived. This is considered the beginning of the modeling and evaluation phase. Next, each system concept is designed/modeled in order to arrive at MOP and, therefore, MOE values. With a determination of system cost, the MOE and cost results are then available for evaluation and/or comparison to other system alternatives. Figure 3-2 shows the full sequence of events for the evaluation process<sup>5</sup>.

The entire process must be completed for the setup of a new problem in order to develop

<sup>5</sup>This AUV system evaluation process was derived from the "early stage ship design process" presented by Hockberger.

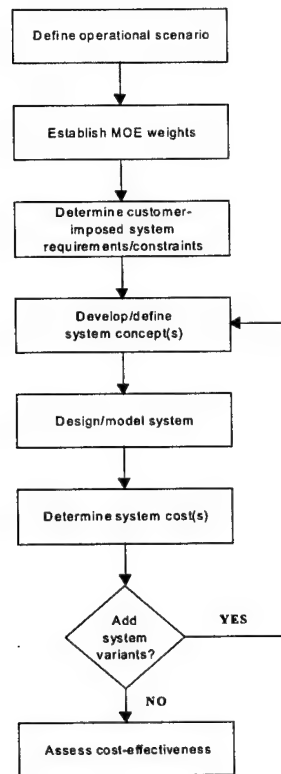


Figure 3-3: Streamlined Evaluation Process Flowchart

the model(s) and establish all necessary relationships. Once this has been done, however, the basic model structure should accommodate any number of evaluation problems that fall under the overall mission. This includes changing the operational scenario, which would require modification to the MOE weights, but should not affect the MOE hierarchy. Depending on the way the lower-level system model was developed, there may be some restriction on the types of AUV systems that it can handle. If this is the case, the system model can be modified or replaced. The only requirement for the system model is that it provide the necessary MOP for determining the mission-specific MOE. The tailored process, for evaluating system alternatives after the initial problem setup, is illustrated in Figure 3-3.

With the overall AUV system evaluation process defined, Sections 3.4 and 3.5 discuss the development of the effectiveness model and system model, respectively.

## **3.4 Effectiveness Model**

### **3.4.1 Overview**

Two main intentions guided the development of an effectiveness model. First, the model would facilitate the broadest possible range of notional underwater vehicle system designs, configurations, and operational employment scenarios. Second, the MOE selected would, so far as possible, be consistent with current or emerging U.S. Navy doctrine. To comply with these intentions, appropriate resources were obtained through Navy contacts and communication was established with other groups engaged in underwater vehicle MCM efforts (see Chapter 2).

The following subsections present the AUV MCM System Effectiveness Model, developed as the first major component of the overall evaluation framework. The proper name "Effectiveness Model" is used to distinguish the particular model developed for the thesis from the more generic effectiveness model previously discussed.

### **3.4.2 Mission and Operational Requirements**

Following the established evaluation process (Figure 3-2), the overall mission was identified as MCM. Assuming that the subject of the entire evaluation framework was AUV MCM systems, the system-specific operational requirements were defined as follows:

1. Conduct MCM operations, including mine reconnaissance (detection, classification, identification, and localization) and mine clearance (neutralization).<sup>6</sup>
2. Conduct operations with minimal reliance on support platforms.
3. Conduct clandestine operations (as needed).
4. Communicate with host platform or entity.

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<sup>6</sup>In official U.S. Navy mine warfare terminology, the four levels of MCM effort are detection, classification, identification, and neutralization. Detection corresponds to discovering an object, classification determines whether the object is minelike or not, identification refers to positive designation as a mine, and neutralization removes the threat. Localization, which an important step for mapping and/or reacquisition of mine contacts, is sometimes included as a fifth level.

### 3.4.3 MOE Determination

The Navy's Program Executive Office for Mine Warfare (PEO(MIW)) defines MOE and MOP that address today's mine warfare practices and systems. These metrics, largely geared toward surface- and air-based MCM systems, are designed to standardize the procedures for data collection and system evaluation throughout the fleet, yet are not intended to be all-inclusive or restrictive [15]. The existing MOE fall short of fully describing the potential capabilities of advanced underwater vehicle MCM systems.

The Effectiveness Model MOE were established by considering the operational requirements for AUV MCM systems and comparing those requirements to the existing MOE to determine where modifications and additions were needed. PEO(MIW) Instruction 3370 [15] defines two force-level MOE: *Time* and *Risk*. The Time MOE refers to the time required to execute the specified mission, while the Risk MOE addresses the vulnerability of transiting platforms and MCM vehicles to the encountered minefield. Depending on the particular application, these MOE are determined from some combination of system/platform-level MOP. The Instruction defines thirty-two MOP. Examples include: sensor probabilities of detection, classification, and identification; probabilities of mine-to-target actuation and subsequent damage; and other platform characteristics such as transit speed to the area, search speed, time to turn, and endurance. A review of the MOE and their application to AUV MCM systems led to the following conclusions:

- Near real-time communications may be desired with the AUV system. The vehicles' abilities to relay information between themselves and to the surface (to a ship or satellite) will need to be measured.
- Covertiness is one of the primary benefits of an AUV system. This trait should be measured and incorporated into a measure of effectiveness.
- AUVs, despite their name, will still require some level of logistics support, for deployment and recovery at least. This impact on the overall system effectiveness must be accounted for.
- Human guidance/oversight of any system imposes demands on manning and other re-

sources, and should be considered during system evaluation.

- Unmanned systems do not possess the same risk characteristics as manned systems. This aspect of the Risk MOE should be examined for possible modification.

Based on the review, three new MOE were incorporated: *Autonomy*, *Communication*, and *Coverttness*. A closer look at some of the contrasts between surface- or air-based MCM systems and underwater-based systems provides some added justification for these new MOE. MCM ships and aircraft today have essentially equivalent communication and coverttness characteristics relative to each other. Their communication abilities are extensive, while their ability to conduct covert operations is almost non-existent. For AUVs, and especially for multiple-vehicle systems, coverttness and communication abilities may vary significantly depending on the composition and configuration of the system. This variability also applies to support/oversight requirements for underwater vehicle systems, whereas conventional systems have fairly uniform requirements.

The existing Time MOE was adopted without modification, except to rename it Mission Time. The Risk MOE, however, was extensively modified and renamed Mission Accomplishment. The Mission Accomplishment MOE focuses on the end condition of the searched or cleared area rather than the vulnerability of transiting or MCM platforms.

These five MOE – *Mission Time*, *Mission Accomplishment*, *Autonomy*, *Communication*, and *Coverttness* – form the upper level of the MOE hierarchy, as shown in Figure 3-4. In anticipation of the need to link these MOE to the system MOP, the MOE were decomposed to form a second level of subordinate MOE. A brief description of each MOE and sub-MOE follows.

### **Mission Time**

The Mission Time MOE represents the time required for the AUV system to complete the assigned mission objectives. This is best expressed in terms of the effective area coverage rate (ACR), expressed in square nautical miles per hour. The effective ACR is defined as the ratio of the total search area to the total amount of time required to complete the mission objective(s), from AUV system deployment to recovery. This includes time spent in the search area plus

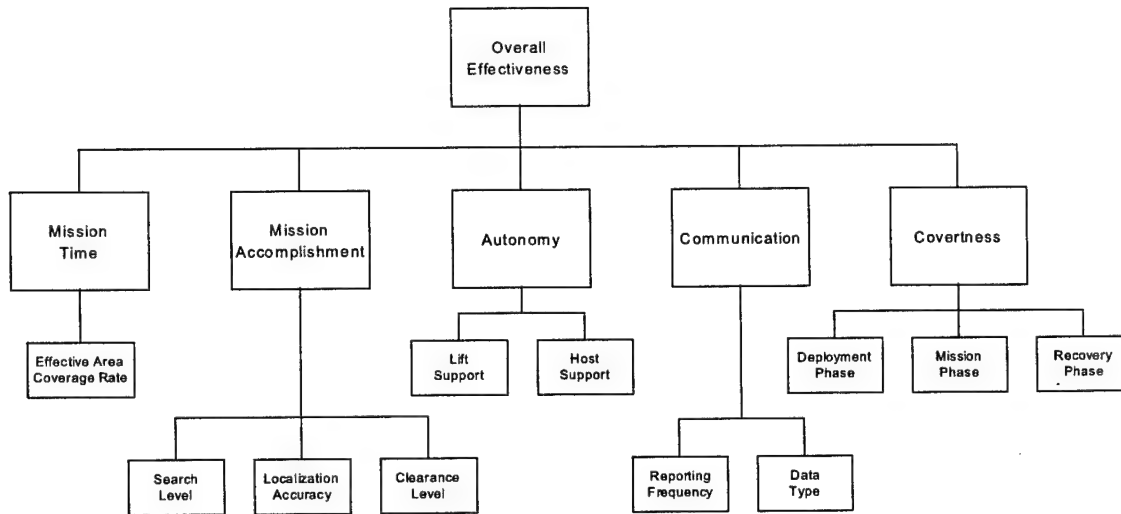


Figure 3-4: AUV MCM System Effectiveness Model Hierarchy

transit time to/from the search area. An alternative sub-MOE is just the total mission time, given in hours.

### Mission Accomplishment

The Mission Accomplishment MOE represents the estimated condition of the searched/cleared area after the mission is completed. This MOE reveals the extent to which any specified mission objectives were achieved or surpassed. The two basic classes of MCM missions are mine reconnaissance and mine clearance. The evaluation framework assumes that, for a given evaluation problem, only one of these missions will be in play. In other words, all systems being evaluated and compared will be operating under the same mission, either reconnaissance or clearance. Two of the three sub-MOE apply to the reconnaissance mission: search level and localization accuracy. For the recon mission, these two sub-MOE are weighted relative to each other, and the clearance level sub-MOE receives a zero weight. Search level refers to the cumulative probability of detecting, classifying, and correctly identifying mines within the specified search area. It is also commonly referred to as “percent search”. Localization accuracy represents the distance error between the reported mine positions and the actual mine positions, or “contact position error”. For this model, the contact position error is taken as a



function of the system navigation error, the latter normally given as a percentage of distance traveled<sup>7</sup>. For a clearance mission, clearance level is given a weight of unity, and the other sub-MOE are zero. Clearance level refers to the cumulative probability of detecting, classifying, identifying (optional), and neutralizing mines within the specified search area, and is also known as "percent clearance". For this thesis, the system model was not developed to describe mine clearance operations.

### **Autonomy**

The Autonomy MOE represents the independence of the system from logistics support and/or oversight for guidance and tasking. Two subordinate MOE comprise the Autonomy MOE: Lift Support and Host Support. Lift support measures the amount of cargo space required for deployment/recovery of the system, given in terms of area (e.g. sqft). Host Support refers to the level of service and/or command and control support required during a mission. This requirement is specified in terms of discrete host responsibility alternatives (e.g. dedicated platform, remote command and control, none, etc.)

### **Communication**

The Communication MOE represents the system's capability to receive and/or transmit mission-related information from/to a host. The Communication MOE is broken down into two subordinate MOE: Reporting Frequency and Data Type. Reporting frequency describes the frequency of transmissions (e.g. number of transmission occurrences per hour) from system to host or vice versa. Data type reflects the type of information being conveyed, particularly referring to whether it is "low content" or "high content" data. Low content data would include CAD/CAC<sup>8</sup>, system position/status, contact positions, as well as command and control-related information from a host. High content data would be post-processed data intended for human interpretation, such as sonar imagery or "snippets".

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<sup>7</sup>If determined by post-analysis or simulation, localization error could be given as Distance Root Mean Squared (DRMS).

<sup>8</sup>CAD/CAC stands for computer-aided detection/classification and refers to the type of data being transmitted.

## Covertness

The Covertness MOE represents the extent to which the system's presence and efforts are difficult to detect. The sub-MOE partition this MOE into three phases: deployment, mission, and recovery. Each sub-MOE represents the ability of the system to avoid detection during that particular phase.

### 3.4.4 MOE Weights

The relative weight assigned to each MOE and sub-MOE should reflect the preferences of the warfighter in relation to the mission and the specific scenario in play. While the warfighter may understand the mission very well and have a feeling of which system operational capabilities are more important than others, converting these subjective "values" into numeric weights is often difficult. The Analytical Hierarchy Process (AHP) provides a useful approach for attempting to establish the correct priorities among decision criteria. The method for establishing the Effectiveness Model MOE weights employs an AHP pairwise comparison technique, whereby the criteria are directly compared to each other (one pair at a time). These direct comparison results are then organized into matrix form, and the actual relative weights are determined from the matrix eigenvector corresponding to the largest eigenvalue [14]. The weighting technique is illustrated below for the five Effectiveness Model MOE.

The first step is to order the MOE by relative importance for the given mission scenario. Recall that it is the warfighter whose preference structure should be extracted, either through surveys or other direct assessment means. For a typical MCM operation, the Mission Time and Mission Accomplishment will be regarded as the most critical parameters, forming the classic MCM trade-off between timely access to (or simply information about) a suspected problem area versus the acceptable risks in terms of loss of life, loss of capital assets, and/or loss of tactical advantage. The specific mission objectives for a given scenario will determine how Mission Time and Mission Accomplishment are weighted relative to each other. The Autonomy, Communication, and Covertness MOE will probably be weighted on a second tier of importance, but still must be compared to the first two. Whatever the case, the ordering of the MOE simplifies the process of assigning importance values during the pairwise comparison. For this example, the order is said to be Mission Time, Mission Accomplishment, Communication,

Autonomy, and Covertness.

Next, each MOE is compared to the other MOE in turn. This can either be done for all combinations of MOE pairs, or just the first round of comparisons, i.e. comparing one MOE to each of the others and then stopping. The AHP process emphasizes the former approach because it tends to more effectively remove bias from the exercise by providing multiple, overlapping opportunities to assign relative importance. After the eigenvalue problem is solved, a mathematical check ensures that enough consistency exists in the pairwise weights. However, the full comparison approach can be time consuming. Beside the number of combinations required, the process may have to be repeated (with revised survey questions or clarification of some sort) in order to get the necessary consistency<sup>9</sup>. The second approach is faster, requiring just  $n-1$  comparisons and resulting in a perfectly consistent matrix; however, the resulting weights may not reflect the warfighter's preference structure as accurately as if all possible pairwise comparisons were made. Following the latter approach for this example, the MOE are assigned comparison values using Time as the reference MOE. The subscripts of the relative importance values,  $RI_{ij}$ , should be read as "the relative importance of i over j", where i and j correspond to the order of the MOE. Time is one, Accomplishment is two, and so forth.

Time vs Accomplishment	$RI_{12} = 1.5$
Time vs Communication	$RI_{13} = 4$
Time vs Autonomy	$RI_{14} = 6$
Time vs Covertness	$RI_{15} = 8$

The remaining  $RI$  values, representing the other six possible MOE pairs, are determined by taking ratios of the first four (if they are not obtained through direct comparison as described above). For example:

$$\text{Accomplishment vs Communication} \quad RI_{23} = \frac{RI_{13}}{RI_{12}} \quad RI_{23} = 2.667$$

Setting up the eigenvalue problem, whose solution will yield the desired MOE weights, the  $RI_{ij}$  values are placed in upper triangular section of a square matrix with columns and rows

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<sup>9</sup>The number of possible pairwise comparisons is  $n(n-1)/2$ , where  $n$  is the number of criteria. The consistency of the comparisons is measured by a parameter called the "inconsistency ratio", which should be less than a specified value [17]. Refer to Appendix C for detailed calculations.

representing the five MOE in the previously established order. Due to the symmetric properties of the matrix, the lower triangular elements are just the reciprocals of the corresponding upper half elements.

$$\text{MOE} = \begin{pmatrix} 1 & 1.5 & 4 & 6 & 8 \\ 0.667 & 1 & 2.667 & 4 & 5.333 \\ 0.25 & 0.375 & 1 & 1.5 & 2 \\ 0.167 & 0.25 & 0.667 & 1 & 1.333 \\ 0.125 & 0.188 & 0.5 & 0.75 & 1 \end{pmatrix} \quad \blacksquare$$

Once the matrix is fully populated, the eigenvalue problem is solved (see Appendix C for details of the matrix solution). The normalized eigenvector associated with the maximum eigenvalue of the matrix contains the MOE weights of interest:

$$\text{MOE\_wt} = \begin{pmatrix} 0.453 \\ 0.302 \\ 0.113 \\ 0.075 \\ 0.057 \end{pmatrix} \quad \blacksquare$$

The AHP weighting method illustrated here can be used for establishing the relative weights on each level of the MOE hierarchy. In the Effectiveness Model, only the upper-level MOE were weighted by this method. The sub-MOE weights are entered directly, since there are no more than three to compare in each case.

## 3.5 System Model

### 3.5.1 Overview

Recall the two main purposes of the system model within the evaluation framework: (1) to provide an environment in which to design/configure a notional AUV system and (2) to determine the system MOP required as input to the Effectiveness Model. A system model could take many forms and serve many additional purposes, as long as it meets these basic requirements. For

this thesis, in keeping with the primary objective of evaluating "advanced search concepts for multiple-AUV MCM," the system model was constructed according to the following philosophy.

The absolute minimum requirements for the model would be to meet the two above-stated requirements of the evaluation framework and to incorporate, to some extent, the capability to handle multi-AUV system concepts. To aid in completing the model within the available timeframe, the operational requirements for the system would be limited to mine reconnaissance (searching and mapping), as opposed to mine clearance, and operational scenarios and tactics would be kept relatively simple. To reduce the burden on the user and facilitate rapid system definition, the model's input requirements would be kept to a minimum by providing databases of vehicle sub-system components whose physical and performance characteristics are relatively well-understood. Finally, time permitting, the model would be scoped so as to allow evaluation of a broad range of AUV system concepts. At the low-capability end, this would include single-vehicle concepts, primarily for comparison reasons. At the high end, the model would handle "cooperative" multi-vehicle concepts, where the presence of multiple vehicles serves to significantly enhance the overall capabilities (and hopefully the cost-effectiveness) of the system.

It is important to emphasize that, for this thesis, the System Model is not intended to accurately represent the physical or performance characteristics of the systems, but rather to provide *consistent* representation of the systems so that they can be evaluated in a relative sense. For real-world applications of the evaluation framework, consistency in the model will still be vital, and accuracy requirements for the system model will depend on the particular evaluation problem.

### **3.5.2 System Model Components**

The AUV System Model, illustrated in Figure 3-5, consists of three modules: *Input Module*, *Mission Planning Module*, and *AUV Design Module*. Within the Input Module, the user specifies the scenario and tactical parameters for the mission, as well as the AUV system configuration and general characteristics. System configuration is entered in terms of the core mission-enabling sub-components for each type of vehicle. These sub-components, referred to as payload, include sensors, navigation units, and communications. The user also specifies the number of each type of vehicle, e.g. one Type A and five Type B.

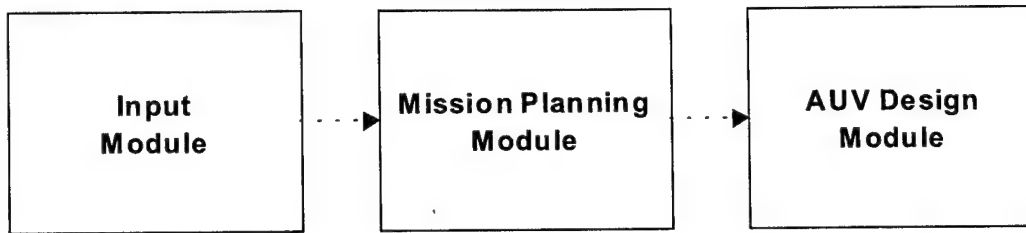


Figure 3-5: AUV System Model

The parameters required by the Input Module are listed in Table 3.1. The inputs are grouped into three categories: *scenario*, *system definition*, and *tactical parameters*. For an evaluation exercise, the scenario parameters are set and left constant while the system definition and tactical parameters are specified for each system alternative. Once the user has completed the initial data entry, certain information routes from the Input Module directly to the Effectiveness Model, while the remaining data is passed to the Mission Planning Module and AUV Design Module for further processing.

The Mission Planning Module performs calculations pertaining to the MCM mission to reveal what is required of the system in order to meet the mission objectives. Specifically, the module determines the level of effort required by the system to achieve the user-specified MCM objectives. For example, if the user desires a percent search of 90% for a given area, the module will determine the number of tracks that the AUV system must run in order to achieve 90%. The number of tracks is a critical parameter for determining the overall mission time. Mission time is the total time required for the system to complete the entire mission, and is also calculated in the Mission Planning Module. It includes the time required to run tracks, prosecute contacts, surface for navigation or communication (if required), and transit to and from the search area. The effective area coverage rate, which is equal to the total search area divided by the total mission time, is also provided by the module. Since the number of tracks is an integer, the predicted percent search that will be achieved will be slightly greater than the objective value, so the achieved percent search is given as an output of the module as well. The inputs and outputs for the Mission Planning Module are shown in Figure 3-6.

It is worth pointing out that the outputs of the Mission Planning Module are actually MOE

Scenario	System Definition	Tactical Parameters
Mission Objectives Percent search Transit distances Transit distances Environment Bottom type category Average water depth Mine Threat Fraction of undetectable mines Assumed mine target strength Estimated number of mines	System-level Requirements Number of vehicle types Host-system comms method Reporting frequency System navigation fix method Contact position error threshold Reliability/redundancy level Battery recharge method Delivery method for clandestine ops Recovery method for clandestine ops Vehicle Requirements and Payload Vehicle type/role Number of vehicles (each type) Surfacing requirement (toggle) Maximum vehicle length Maximum vehicle diameter Maximum vehicle deadweight Sonar type(s) Navigation package Communication package Computer/processor Battery type	Speed Search speed Transit speed Search Parameters Vehicle altitudes Number of runs/track Sonar Performance Parameters Characteristic search width Characteristic probability of detect/class Probability of identification Navigation Performance Position error Standard deviation of track keeping

Table 3.1: Input Module Parameters

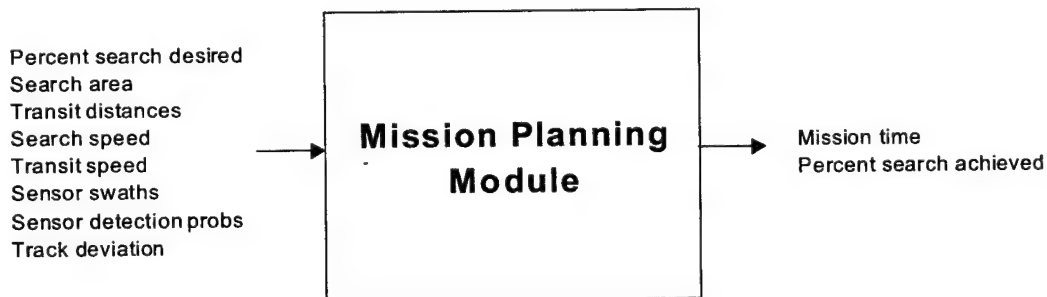


Figure 3-6: Mission Planning Module Inputs and Outputs

that have been determined through modeling (as opposed to direct assessment), taking into account certain mission parameters. Admittedly, the inclusion of mission-oriented calculations in the system model is a deviation from the originally-stated approach. The reason for this deviation is to maintain consistency between the systems being evaluated by requiring some of the system parameters to be specified as objectives and to apply those objectives to all the systems being considered. This constrains the problem somewhat, forcing the values of certain parameters for each system to comply with the desired common objectives. As shown in Table 3-6, the user-specified objectives for this model are percent search, search area, and transit distances. The System Model combines the given values with internally calculated time results to arrive at the total mission time. Mission time is then used as a reference for the endurance of the multi-AUV system, and therefore the endurance of each AUV within the system. The endurance of the system is fixed in this manner so that all systems being compared can be said to have just enough endurance to complete the mission (with some uniform margin built in, if desired).

The AUV Design Module designs the individual AUVs based on the user-specified payload items and the results of the Mission Planning Module. This is done primarily to provide a reasonable estimate of vehicle sizes required to accommodate the payloads and meet the endurance requirement. The AUV Design Module was developed by modifying a parametric-based submarine design model<sup>10</sup> currently used at MIT. The AUV version of the model performs three main engineering "balances": volume required versus available, weight versus buoyancy, and speed versus power. For the volume balance, the module allows the user to adjust the vehicles dimensions and shape, essentially wrapping a shell around the payload components (sensor/navigation/communication/computer packages and battery), until the available volume/displacement meets or exceeds that which is required. Vehicle weights are then estimated, and ballast requirements are calculated to achieve a desired buoyancy condition. For powering, the Module performs resistance calculations to determine the amount of energy (i.e. battery size/weight) required to meet the specified speed and endurance for the mission. The user

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<sup>10</sup>The MIT SSN (attack submarine) Math Model is a Mathcad-based tool used for design courses in the Naval Construction and Engineering Program (13A). The original model, developed in 1995, was based on design parametrics developed by CAPT Harry Jackson, USN (Ret). The model has been updated by students and faculty over the last several years. The AUV version of the follows the general procedure of the SSN Model, but is greatly simplified and uses only a few of the same parametric relationships.



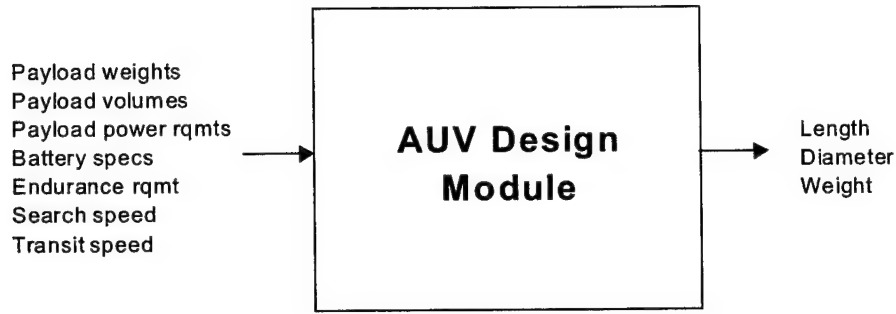


Figure 3-7: AUV Design Module Inputs and Outputs

iterates through the model to achieve an overall balance. Figure 3-7 summarizes the inputs and outputs for the AUV Design Module.

### 3.5.3 System Model MOP

For an AUV system modeled as described in the preceding paragraphs, the MOP should include all of the highest-level system physical and performance characteristics. As alluded to in the discussion of the Mission Planning Module, it is sometimes difficult to sort out the MOE and MOP, especially when the MOE are determined through modeling rather than utility functions. For this thesis, the rule-of-thumb for distinguishing between MOE and MOP has been to ask whether or not the parameter is purely system-dependent, or whether it depends on external, mission-related factors. In keeping with this, the MOP corresponding to each MOE were identified. Table 3.2 summarizes the MOP for each sub-MOE.

## 3.6 The Integrated AUV MCM System Evaluation Model

Bringing the System Model and Effectiveness Model together forms the Integrated AUV MCM System Evaluation Model. This framework permits the evaluation of notional AUV MCM systems in the context of overall mission-effectiveness. Incorporating cost, the mission-effectiveness of the systems are weighed against the costs that are considered paramount, providing a firm basis for decision-making. Figure 3-8 illustrates the Integrated AUV MCM System Evaluation

MOE (Subordinates)	MOP
Effective Coverage Rate	Search Speed (knots)
	Transit Speed (knots)
Search Level	Characteristic search width (yards)
	Characteristic probability of detection/classification (percent)
	Probability of identification (percent)
	Standard deviation of track keeping (yards)
Localization Accuracy	Navigation position error (% distance traveled)
Lift Support	System footprint (sqft)
Host Support	Platform requirement (levels)
Reporting Frequency	Reporting opportunities (levels)
Data Type	Data content (levels)
Deployment Phase	Platform type (levels)
Mission Phase	Platform type and standoff distance (levels)
Recovery Phase	Platform type (levels)

Table 3.2: System Model MOP Corresponding to Effectiveness Model MOE

Model.

### 3.6.1 MOE-MOP Relationships

The critical aspect of the Evaluation Model is the link between the MOE and MOP. Section 3.2 discussed two general methods for determining MOE from MOP: modeling/simulation and direct assessment. For each MOE, the choice of translation method depends not only on the type of information that is available from the system model, but whether a non-subjective relationship between the system parameters and the MOE can be determined. If such a valid relationship can be established with a reasonable amount of effort, then modeling/simulation is the best choice. If not, a general (subjective) relationship, derived from direct assessment of the warfighter's preferences, should be used. The Evaluation Model MOE-MOP relationships were forged according to these criteria. Table 3.3 summarizes the method of translation for each MOE-MOP set and lists, in the fourth column, the primary mission-related parameters and considerations that contribute to the relationships. In following subsections, the MOE-MOP relationships are presented. It is emphasized that the subjective relationships must be based on the warfighter's preferences in order to be valid. For this thesis, no surveys or other means of assessment were conducted. For all subjective MOE-MOP relationships, the MOE scores corresponding to the MOP inputs were assigned by the author and are meant to be

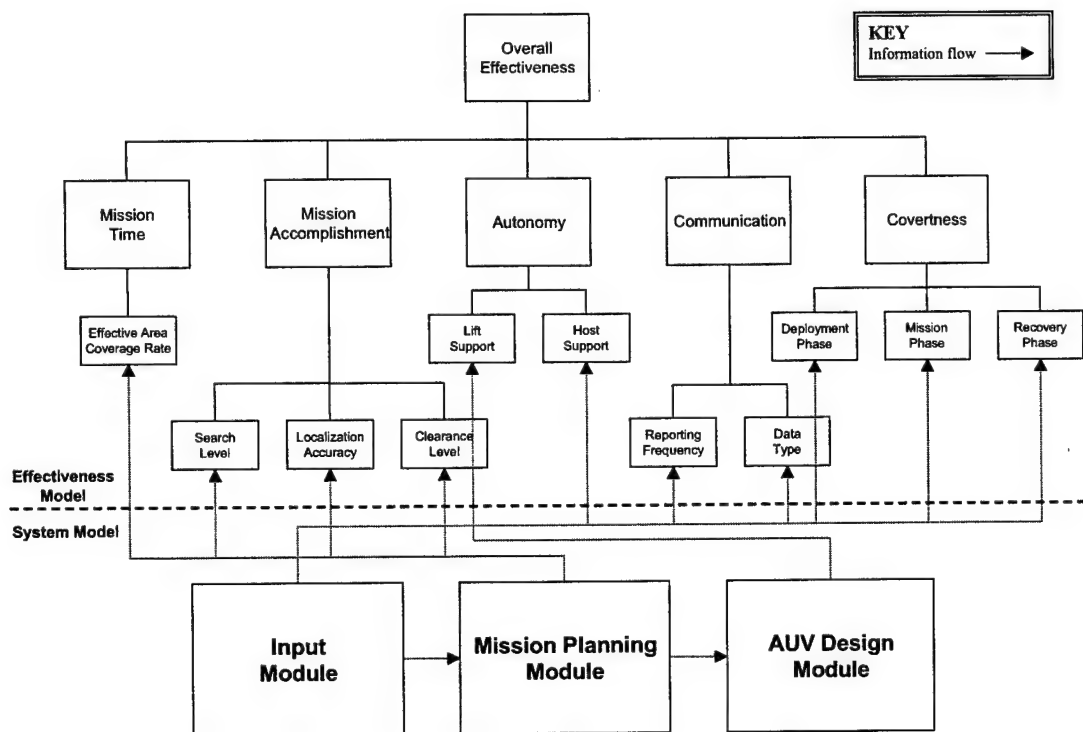


Figure 3-8: Integrated AUV MCM System Evaluation Model

Sub-MOE	MOP	MOE-MOP Translation	Mission Parameters
Effective Coverage Rate	Search Speed (knots) Transit Speed (knots)	Modeling	Search area Number of tracks Est. number of mines
Search Level	Characteristic search width (yards) Characteristic probability of detection/classification (percent) Probability of identification (percent) Standard deviation of track keeping (yards)	Modeling	Target strength Bottom type Sonar parameters Water depth
Localization Accuracy	Navigation position error (% distance traveled)	Modeling	Contact position error threshold
Lift Support	System footprint (sqft)	Modeling	Space restrictions; impact on other missions
Host Support	Platform requirement (levels)	Subjective relationship	Impact of host reqmt on other mission
Reporting Frequency	Reporting opportunities (levels)	Subjective relationship	Degree of need for host-system communication
Data Type	Data content (levels)	Subjective relationship	Degree of need for certain information types/formats
Deployment Phase	Platform type (levels)	Subjective relationship	Desire to avoid detection
Mission Phase	Platform type and standoff distance (levels)	Subjective relationship	Desire to avoid detection
Recovery Phase	Platform type (levels)	Subjective relationship	Desire to avoid detection

Table 3.3: MOE-MOP Translation Summary

representative only.

### MOE-MOP Relationships for Mission Time

Effective Area Coverage Rate is the sub-MOE used to describe the Mission Time MOE. It is equal to the search area divided by the total mission time. Total mission time is determined from the system's speed and associated distance traveled during each segment of the operation. For this model, the time segments are: transit time, search time, navigation/communication excursion time, and prosecution time. Equation 3.1 applies.

$$ACR_{eff} = \frac{L_{searcharea} \cdot W_{searcharea}}{T_{mission}} \quad (3.1)$$

where,

$ACR_{eff}$  = Effective area coverage rate

$$L_{searcharea} \cdot W_{searcharea} = \text{Search area}$$

$$T_{mission} = \text{Total mission time}$$

The individual time calculations must be tailored to the type of operation being conducted, as well as the tactics employed. The details of these calculations for the Evaluation Model can be found in Appendix C. The source of Equation 3.1 is reference [15].

### MOE-MOP Relationships for Mission Accomplishment

For the minehunting problem, the Mission Accomplishment MOE receives its score from the Search Level and Localization Accuracy sub-MOE. The selected approach for predicting Search Level, or percent search, is based on an "approximation theory" developed by the Navy in the 1960s. This approach, outlined in PEO(MIW) Instruction 3370 [15], remains the standard method for estimating search and/or clearance levels for U.S. Navy MCM operations. It applies to uniform coverage over a set of parallel tracks. The governing relationships, as applied to the minehunting problem for this thesis, are summarized as follows. The equation for percent search is:

$$P_{search} = (1 - \mu) \cdot P_{imm} \cdot (1 - e^{-M \cdot Y}) \quad (3.2)$$

where,

$P_{search}$  = Percent search through identification

$\mu$  = Fraction of undetectable mines

$P_{imm}$  = Probability of identifying a mine as a mine

-  $M = \frac{J \cdot A \cdot B}{D_{track}}$  = Combined measure of area coverage level and detect/class success

$J$  = Number of runs per track

$A$  = Sensor characteristic search width

$B$  = Characteristic probability of detection/classification

$D_{track}$  = Distance between tracks

$$Y = -\frac{2 \cdot \sigma}{A \cdot B} \cdot \int_0^{\infty} \ln[1 - B \cdot (cnorm(u + \frac{A}{2 \cdot \sigma}) - (cnorm(u - \frac{A}{2 \cdot \sigma})))] du$$

$Y$  = Coefficient of MCM efficiency

$\sigma$  = Standard deviation of track keeping error

$cnorm(x)$  = Value of the cumulative normal distribution function at  $x$

Localization Accuracy is determined in a much more straight-forward manner. A general assumption is made that the AUV MCM system will have some means of fixing its position periodically in order to navigate along the intended tracks. The System Model requires an entry for the maximum acceptable contact position error at any point during the search effort. Ignoring any error due to the sensor, and assuming further that the position error of the AUV grows linearly with time (i.e. as a percentage of distance traveled), the average contact position error over the course of the search should be approximately one half of the maximum position error:

$$avg\_pos\_error = 0.5 * max\_pos\_error \quad (3.3)$$

### MOE-MOP Relationships for Autonomy

The sub-MOE for Autonomy are Lift Support and Host Support. Because Lift Support refers to the inconvenience or other costs associated with transporting the AUV system to/from the mission area, a reasonable metric is the system cargo area requirement, or footprint. The footprint is determined from Equation 3.4:

$$FP_{sys} = \sum_{i=1}^{numtype} f_{stow_i} \cdot numveh_i \cdot FP_{veh_i} \quad (3.4)$$

where,

$FP_{sys}$  = Total AUV system footprint, or required cargo area

$numtype$  = Number of vehicle types in system

$f_{stow_i}$  = Stowage factor (fraction multiplier) for vehicle type  $i$

$numveh_i$  = Number of vehicles of the  $i^{th}$  type

$FP_{veh_i}$  = Footprint of  $i^{th}$  vehicle type

Host Support is meant to reflect the level of service and/or command and control support required during a mission. This sub-MOE, and in fact all of the remaining sub-MOE, are governed by completely subjective relationships as opposed to mathematical formulas. For example, Host Support is specified in terms of discrete host responsibility alternatives: dedi-

cated platform, remote command and control, and none required. Presumably, these levels of support have definite meaning to the warfighter, with "none required" being the ideal case and "dedicated platform" the worst. To figure out which case applies to the particular AUV system being evaluated, condition statements are used. The conditions are specific system characteristics that would cause a certain type of support to be required. In the Effectiveness Model, these conditional statements are written in terms of system parameters whose "values" are discrete designators, each of which represents a system characteristic. For all of the sub-MOE, these characteristics are specified as inputs, during system definition, so that the possible outcomes are set in advance. Table 3.4 lists the conditions that determine each level of the Host Support sub-MOE.

Host Support Level	Condition(s)
Dedicated or in-theater support	Reliability = "low" OR Communications method = "acoustic modem" OR Communications method = "RF line of sight" OR Battery recharge method = "host"
Remote command and control	Communications method = "RF via satellite"
None required	Otherwise

Table 3.4: Conditions for Determining Host Support MOE Levels

### MOE-MOP Relationships for Communication

The two sub-MOE for Communication, pertaining to how often communication occurs and how valuable the data is, are determined from system-level requirements specified in the Input Module. Tables 3.5 and 3.6 present the levels and conditions for Reporting Frequency and Data Type, respectively.

Reporting Frequency Level	Condition(s)
None	Reporting frequency = "not required"
Periodic	Communications method = "periodic"
Continuous	Otherwise

Table 3.5: Conditions for Determining Reporting Frequency MOE Levels

Data Type Level	Condition(s)
None	Communications method = "none required"
Low-content data	Communications method = "acoustic modem"
High-content data	Otherwise

Table 3.6: Conditions for Determining Data Type MOE Levels

### MOE-MOP Relationships for Coverttness

For Coverttness, the sub-MOE represent the likelihood of avoiding detection during any of three operational phases: Deployment Phase, Mission Phase, Recovery Phase. The ability of an AUV system to avoid detection will depend on many factors, including signatures (e.g. magnetic, acoustic, radar cross-section, etc.) and time spent in the area of concern. These factors apply not only to the AUV system, but also to its host platform, if applicable. To develop concise relationships for these sub-MOE, the problem was simplified by linking the level of coverttness to the type of host platform required to support the AUV system during each of the three mission phases. In the case of the Mission Phase sub-MOE, the location of the platform (i.e. the proximity to the area of concern) is also factored in. This simplification assumes a significant relative difference between the signatures of the AUV system and the host platform. Three platform types are used in the relationships: surface, sub-surface, and air. For Mission Phase, the relationship is modified slightly so that it corresponds to the type of host platform required for the search. Tables 3.7 through 3.9 show the relationships.

Delivery Phase Level	Condition(s)
Surface ship	Delivery method = "surf"
Aircraft	Delivery method = "air"
Submarine	Delivery method = "sub"
None required	Delivery method = "not required"

Table 3.7: Conditions for Determining Delivery Phase MOE Levels

### 3.6.2 MOE Scoring and Interpretation

Having established all MOE-MOP relationships for the Evaluation Model, the final task in the model's development is to ensure the MOE are presented in a useful manner. Using the



Mission Phase Level	Condition(s)
Surface ship	Otherwise (none of the below conditions)
Submarine	Delivery method = "sub"
Satellite/air link	Host Support Level = NOT "none required" AND NOT "dedicated/in-theater support"
None required	Host Support Level = "none required"

Table 3.8: Conditions for Determining Mission Phase MOE Levels

Recovery Phase Level	Condition(s)
Surface ship	Delivery method = "surf"
Aircraft	Delivery method = "air"
Submarine	Delivery method = "sub"
None required	Delivery method = "not required"

Table 3.9: Conditions for Determining Recovery Phase MOE Levels

MOE results obtained above, comparison of even a small number of systems would be difficult because of the variation in the way the MOE "values" are stated. Effective Coverage Rate, Search Level, Localization Accuracy, and Lift Support have real numeric values with associated units. The others are given as levels of capability or action that contribute to the mission. In many cases, a uniform scale of measure is desirable for comparison of sub-MOE between systems. Furthermore, such a scale is required in order to incorporate the MOE and sub-MOE weights. This, after all, is the main purpose of the effectiveness hierarchy (recall Figure 3-4). Still, for some comparisons, a mix of scaled and real values may be useful, as shown in the case demonstrations (Chapter 4).

A simple means of scaling a parameter is to establish lower and upper bounds, assign them a score of 0 and 1, respectively, and then determine how the intermediate values of the parameter are scored on that scale. The result is a utility function which translates the original parameter value into a score between 0 and 1. If linear scaling is appropriate, the score for any intermediate value is determined by Equation 3.5:

$$ScaledValue = (intermediate\_value - low\_value) / (high\_value - low\_value) \quad (3.5)$$

For situations where desired output does not vary linearly with the input, a non-linear utility function is required. While not used in the Evaluation Model, one formal method for determining non-linear relationships is mentioned because of the possible applicability to future developments of the model. The technique follows the AHP pairwise comparison matrix procedure used to establish the MOE weights (Section 3.4.4), except that the eigenvector is scaled according to Equation 3.5 (rather than normalized). For this application, the row and column entries correspond to selected input parameter values instead of MOE, and it is those input values whose importance is compared in pairs to populate the matrix. The result is a piecewise-linear utility function that accounts for the macroscopic non-linearity of the relationship, but is linear between the values used for the comparison. Reference [14] provides details on this approach.

Getting back to the Evaluation Model, the sub-MOE are scored as follows. For the sub-MOE that are given in terms of levels, scores of 0 and 1 are assigned to the least and most desirable levels, respectively. Because there are only a few, discrete intermediate levels to be scored, the scores can be directly assigned according to the warfighter's preferences. For these sub-MOE, the scores are built into the MOE calculations because the named levels are more cumbersome for comparison purposes. For the remaining sub-MOE – those with real values initially – linear scaling is assumed, but not applied inside the Effectiveness Model. Instead, this is done in a separate spreadsheet, using Equation 3.5, only when the scores are to be multiplied by their associated sub-MOE weights (see end of Appendix C).

To incorporate the MOE weights, the appropriately scaled sub-MOE are multiplied by their individual weights. The weighted scores under each MOE are then summed, and the five MOE weighted sums are added to obtain the overall MOE (OMOE). This single score now represents the entire AUV system on a scale of 0 to 1. The OMOE scores for a large number of systems can be plotted against an independent parameter, such as cost, to guide the evaluator(s) toward a decision as to which system or systems exhibit the best cost-effectiveness mix.

### 3.6.3 Implementation and Use

The Evaluation Model is implemented in a series of worksheets (i.e. files) residing in two computer software programs: Mathcad<sup>11</sup> and Excel<sup>12</sup>. The files are linked together using compatibility features of the two programs. Nearly all of the analytical calculations are performed by Mathcad, with Excel being used mostly for databasing, user entry, and graphical display of results. Mathcad was selected over other computing programs/languages, such as Matlab and Fortran, as much for its abilities as for its “what you see is what you get” presentation attributes. Equations, text, and graphics entered in the worksheet appear very much like you would see them on a blackboard or in a textbook. The highly visual nature of the model is intended to facilitate interpretation and understanding of the model’s underlying methodology so that future developments and extensions of the evaluation approach are not hindered by hard-to-follow programming codes. Appendix A contains a summary of the programmatic details of the Evaluation Model, including a “wiring diagram” which illustrates how the various files are connected. Appendices B and C contain the System Model and Effectiveness Model, respectively. Appendix D contains AUV sub-system databases for the System Model.

Having defined and presented the major components and relationships of the Evaluation Model, a more practical aspect of the model is now addressed: its use. In Section 3.3, the evaluation process was described (reference Figures 3-2 and 3-3). Figure 3-8 in Section 3.6 summarizes the Evaluation Model, showing the connection between the System and Effectiveness Models. Merging the evaluation process and model architecture diagrams, Figure 3-9 illustrates the evaluation process in the context of the modeling environment. Guided by this process, a typical AUV MCM system evaluation problem involves defining a series of system concepts, modeling each system to obtain MOE and cost results, and comparing the outcomes to reach a conclusion or decision. Chapter 4 further discusses the use of the Evaluation Model and the application of the evaluation framework as a whole.

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<sup>11</sup>Mathcad 2000 Professional, by Mathsoft, Inc.

<sup>12</sup>Microsoft Excel 97, by Microsoft Corporation.

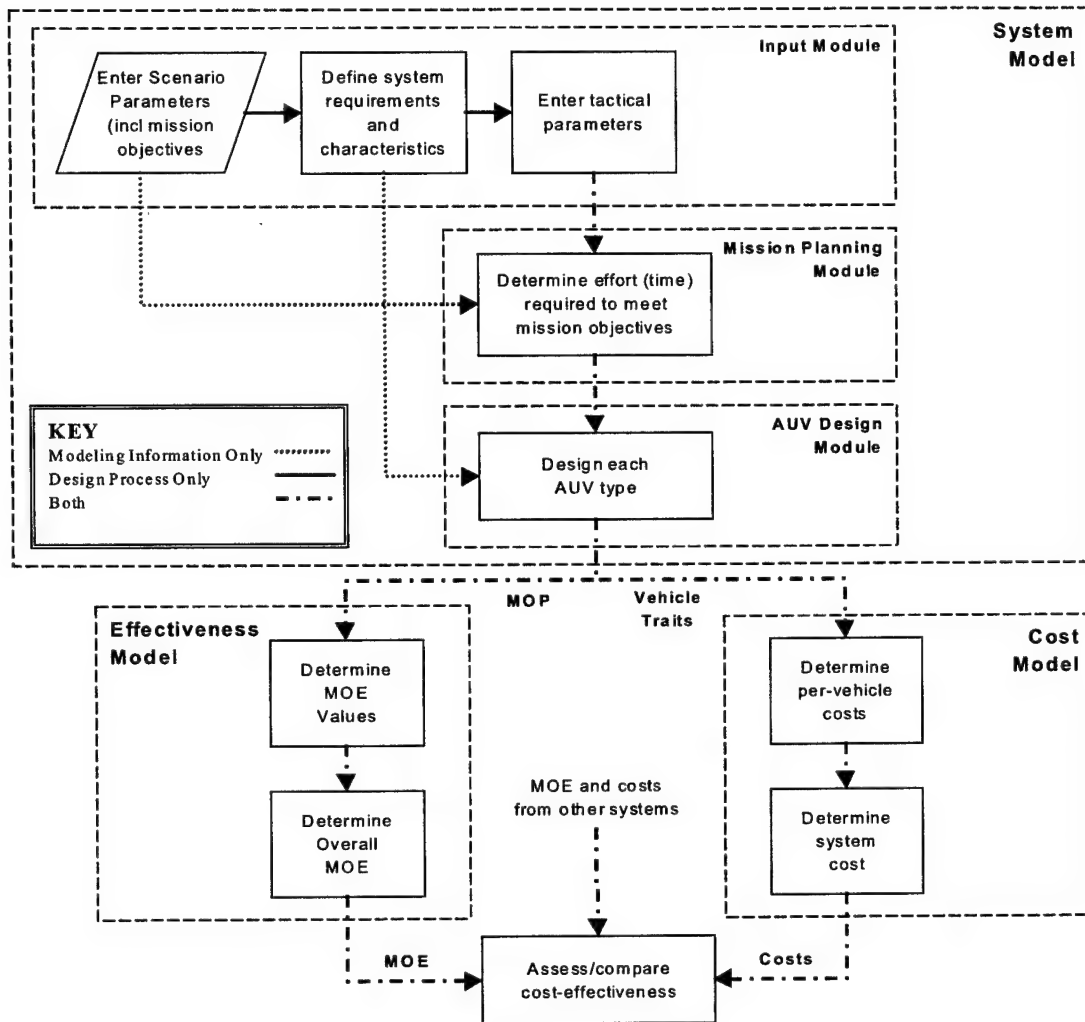


Figure 3-9: AUV MCM System Evaluation Flowchart

## Chapter 4

# Case Demonstrations

The primary purpose of the case demonstrations is to show, through simple examples, the basic features of the Evaluation Model and the manner in which results are obtained. The secondary purpose is to demonstrate the use of the model for two particular types of evaluation problems. In observing and discussing the results, the emphasis is placed on the *nature* of the outputs (rather than the actual values) and how they can assist the evaluator in reaching the sought-after decision and/or conclusions. It is important to note that, for both cases, the results themselves are based on non-validated technical information within the System Model and borrowed cost model, and so should be thought of as representative only.

### 4.1 Case One

#### 4.1.1 Case One Definition

The first case compares two AUV MCM system concepts that have very similar system-level requirements and sub-system components (i.e. sensor types, navigation packages, etc.), but are composed and configured quite differently. Presumably, the evaluator or decision maker is interested in identifying the key differences between each system, in terms of mission effectiveness, and then weighing those differences against the cost(s) of each system. This type of comparison exercise would likely be conducted by designers in the early phase of an AUV MCM system design, perhaps to initially scope the trade-space or to down-select among a set of broad concept alternatives.

Mission objectives	
Percent Search	94%
Search area dimensions	Length: 4 nautical miles
	Width: 4000 yards
Transit distances	Ingress: 0 nautical miles
	Egress: 10 nautical miles
Environment	
Bottom type category	4 (gravel)
Average water depth	400 feet
Mine threat	
Number of mines (estimate)	25
Fraction of undetectable mines	0
Mine target strength	-30 decibels

Table 4.1: Case One Scenario Inputs

The analysis follows the procedure depicted in Figure 3-3. First, a fixed scenario is developed for the evaluation and the MOE weights established for that scenario. Next, the system concepts are defined by specifying the appropriate parameters for each system. Once the system definition is completed, mission planning calculations are performed to determine the total mission time required to achieve the desired search objectives. Each AUV type is then designed to carry the required payload components and meet the endurance requirements demanded by the mission time requirement. From the system characteristics, the effectiveness and cost of each are determined and compared.

The case scenario is based on a mine reconnaissance mission requiring a clandestine search in a 4 x 2 nautical mile area near the coast of enemy-occupied territory. An estimate of the number of mines and their average target strength is obtained through intelligence sources. The bottom type is known to be gravel, and the average water depth in the area is 400 feet. The concept of operations calls for the AUV system to be air-dropped adjacent to the search area, and picked up via surface ship after the mission at a rendezvous point 10 nautical miles from the area. Table 4.1 contains the input values for the scenario parameters.

For this scenario, the MOE and sub-MOE weights are established as described in Section 3.4.4. Referring to Table 4.2, the imaginary warfighter (a role played by the author for this case demonstration) regards Time and Mission Accomplishment as markedly more important than the other three upper-level MOE. The relative weightings for sub-MOE reveal that certain

MOE	MOE Weight	Sub-MOE	Sub-MOE Weight
Time	0.45	Effective Area Coverage Rate	1.00
Mission Accomplishment	0.30	Search Level	0.60
		Localization Accuracy	0.40
Autonomy	0.08	Lift Support	0.25
		Host Support	0.75
Communication	0.11	Reporting Frequency	0.30
		Data Type	0.70
Coverttness	0.06	Deployment Phase	0.40
		Mission Phase	0.35
		Recovery Phase	0.25

Table 4.2: Case One MOE Weights

aspects of each top-level MOE are considered more important than others, such as the level of host support over lift support and type of contact data/information over the frequency of the contact reports.

Two AUV MCM system concepts are evaluated. System One (S1) consists of a single AUV with several minehunting sensors, a robust navigation package, and radio frequency (RF) satellite communications gear. System Two consists of two different vehicle types, one of one type and two of the other, designed to operate as a cohesive unit. For the most part, System Two (S2) contains the same sensors, navigation units, communications gear, and other AUV sub-systems as System One. In this case, however, these sub-systems are distributed between the two AUV types. Vehicle Type One (V1) is designated as the "guide". It possesses an ahead-looking sonar (ALS) and the same navigation and communication packages as the AUV in S1. It operates closer to the surface than the other vehicles in S2, allowing it to surface regularly for GPS fixes and RF communication without incurring the significant time delays it would if operating at a deeper depth. Vehicle Type Two (V2) houses a side-scan sonar for mine detection and classification, as well as a small video camera for identification (ID). For navigation, it has a basic gyro-compass and doppler velocity sensor (DVS), but does not have the capability to fix its position. Instead, it relies on the guide (V1), maintaining station relative to V1 using an acoustic tracking system similar to an ultra-short baseline (USBL) array. The two vehicles of this type operate close to the bottom, at the optimum depth for the side-scan sonar, relaying contact data and imagery acoustically to the lead vehicle (for post-processing and further relay to the host). The system-level requirements/characteristics for S1 and S2 are

identical, except for the number of vehicle types, of course. Table 4.3 summarizes the system definition.

Table 4.4 displays the tactical parameters for S1 and S2. The sonar performance metrics for minehunting are given in terms of characteristic search width, A; probability of detection/classification, B; probability of identification; and false contact density (for classification) [15]. "A" and "B" are simplified parameters describing the effective swath of a sensor (A) and the associated joint probability of mine detection and classification (B). These values depend on parameters like sensor altitude, water depth, bottom type, and mine type. Likewise, "A" and "B" and the other sensing performance parameters are affected by information exchange between sensors. This is why, for S2, the side-scan sonar performance values are slightly higher than for the same sonar in the case of S1. S2 was configured so as to achieve increased performance by using multiple, cooperating vehicles<sup>1</sup>.

The inputs in Tables 4.1 through 4.4 were entered in the Input Module using the Mathcad-Excel program interface.

#### **4.1.2 Case One Results**

Following the entry of required case inputs, Systems One and Two were run through the Evaluation Model one at a time. Costs for each system were estimated using the costing feature of the MCM Future Systems Working Group's UUV Endurance Model. The results of each run were collected in an Excel output file for the comparison. Table 4.5 summarizes the results numerically.

The results are a mixture of real values (with units) and non-dimensional scores (on a scale of 0 to 1). The former are largely the products of modeling to obtain MOE from MOP, while the latter are the result of MOP-MOE utility functions. Because of the manner in which the systems were defined, many of the parameters achieve the same MOE scores. The interesting comparisons are found in the effective area coverage rate, localization accuracy, lift requirement, and, of course, cost. Figure 4-1 illustrates a head-to-head comparison of these parameters.

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<sup>1</sup>For System Two, the search width, A, of 588 yards is the assumed effective swath for the two side-scan sonars (one on each of the V2 AUVs) operating on adjacent tracks. The search width and operating altitude for V2 were intentionally set so that the effective "A" of the following V2 AUVs matched the "A" of the V1 AUV.



System Definition Parameters	SYSTEM ONE Single Vehicle, Multiple Sensor		SYSTEM TWO Multiple Vehicles, Distributed Sensors
Number of vehicle types	1		2
Host-system comms method	RF link via satellite or aircraft		same
Reporting frequency	Periodic		same
System navigation fix method	GPS via periodic surfacing		same
Contact position error threshold (yards)	30		same
Reliability/redundancy level	low - in-theater support required		same
Battery recharge method	not required		same
Delivery method	Air		same
Recovery method	Surface		same
Vehicle Types	S1V1: "LoneAUV"	S2V1: "Guide"	S2V2: "Hunter"
Number of vehicles, each type	1	1	2
Surfacing requirement?	Yes	Yes	No
Maximum length (feet)	20	20	20
Maximum diameter (inches)	21	21	21
Maximum weight (pounds)	500	500	500
Sonar suite	(1) ahead-looking sonar (1) side-scan sonar	(1) ahead-looking sonar	(1) side-scan sonar
Identification sensors	Video camera	None	Video camera
Navigation suite	INS + DVS + GPS	INS + DVS + GPS	DR + DVS + acoustic tracker
Communication suite	RF antenna + acoustic modem	RF antenna + acoustic modem	acoustic modem
Computer/processor	Basic guidance and control, kalman filter, sonar post-processor	Same as System One	Basic guidance and control
Battery type	Silver-zinc	Silver-zinc	Silver-zinc

Table 4.3: Case One System Definition Inputs

Tactical Parameters	SYSTEM ONE		SYSTEM TWO
	Single Vehicle, Sensors	Multiple	Multiple Vehicles, Distrib- uted Sensors
Search velocity (knots)	6		6
Transit velocity (knots)	10		10
Navigation accuracy (% DT)	0.05		0.05
Vehicle Types	S1V1: "LoneAUV"	S2V1: "Guide"	S2V2: "Hunter"
Vehicle Altitude (feet from bottom)	300	350	100
Search width, A (yards)	ALS: 588 SS: 400	ALS: 588	SS: 588
Probability of detection/classification, B	ALS: 0.8756 SS: 0.80	ALS: 0.8756	SS: 0.90
Probability identification	0.95	N/A	0.95
False contact density (per sqnm)	1.0	N/A	0.5
Track keeping accuracy (yards)	5	5	10

Table 4.4: Case One Tactical Parameter Inputs

Sub-MOE	System 1	System 2
Effective Area Coverage Rate (sqnm/hr)	0.48	0.77
Percent Search	0.977	0.977
Localization Accuracy (yds)	15.0	15.0
Lift Requirement (sqft)	18.4	34.7
Host Requirement	0.0	0.0
Reporting Frequency	0.7	0.7
Data Type	1.0	1.0
Deployment Phase	0.3	0.3
Mission Phase	0.0	0.0
Recovery Phase	0.0	0.0
Costs		
Production (\$)	225,167	280,802
Research and Development (\$)	492,791	951,554
Total System Cost (\$)	717,958	1,232,356

Table 4.5: Case One Results

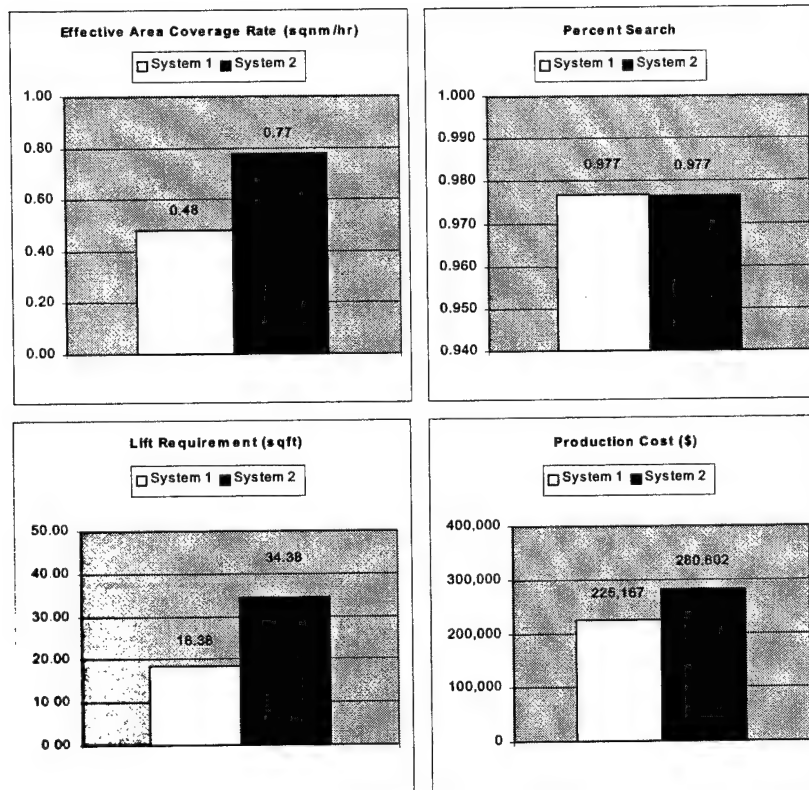


Figure 4-1: Comparison of Select Parameters for Case One

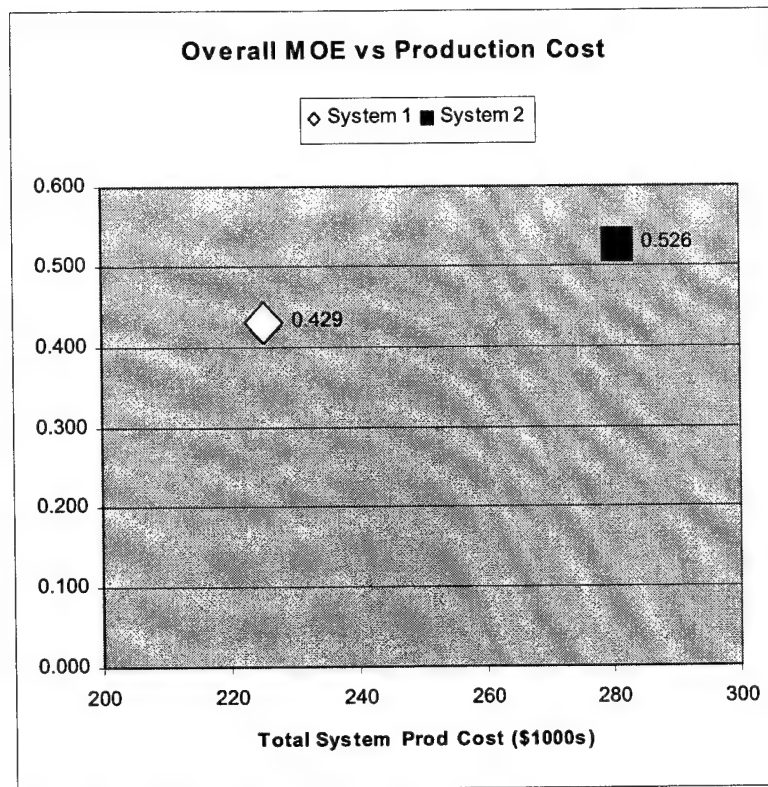


Figure 4-2: OMOE vs. Cost Plot for Case One

Up to this point, the results obtained for each system are given in terms of the lower-level MOE with no accounting for the weights previously established. For this example, a decision could possibly be made from the non-weighted results because only a few of them need to be compared and the decision-maker can apply their preference weighting mentally. For more complex situations, however, the weights may need to be formally incorporated into the results. One way to include the effect of the weights is to normalize each of the values on a 0 to 1 scale (if not already scaled) and then multiply the scores by the weights, as described in Section 3.6.2. These weighted scores can then be rolled up into the overall MOE (OMOE) and plotted against some independent parameter such as cost, as done in Figure 4-2.

The OMOE versus cost approach is attractive in the sense that it simplifies the analysis down to just two parameters for each system. The problem, though, is that a decision-maker probably can't look at just two (or even a few) OMOE values and reach a conclusion as to

which alternative is most cost-effective. Unless the person evaluating the plot has a very good understanding of the model being used, and has observed the dynamics of the OMOE value as system parameters are altered, they will not be able to decide what OMOE difference is worth the associated cost difference. The OMOE versus cost plot is much more conducive to comparing a larger number of system alternatives. Case Two, which examines five system variants, provides a better opportunity to use the OMOE versus cost plot.

## **4.2 Case Two**

### **4.2.1 Case Two Definition**

The Evaluation Model may be useful for exploring large sets of system concepts, where the number of systems makes direct parameter comparisons too difficult. Case Two examines a situation where the evaluator is trying to determine the effect (on cost and effectiveness) of slightly varying the mix of vehicles in the systems. The mission, scenario, and MOE weights from Case One apply. Five variants are formed by selecting from a pool of three basic vehicle types, each possessing their own baseline capabilities but configurable for a particular role in a system. For each variant, the number of vehicles and their role (i.e. sensing only, navigation/communication only, or both) are also varied. Tables 4.6 and 4.7 summarize the system definition and tactical parameter inputs<sup>14</sup>.

### **4.2.2 Case Two Results**

The results for Case Two are presented in Table 4.8 and Figures 4-3 and 4-4. The formats are identical to Case One, but several additional parameters are plotted to capture all of the interesting differences for this case. With five system variants, the direct comparison plots (Figure 4-3) reveal significant differences between the systems, but do little to help the evaluator decide which is the most cost-effective (especially if the MOE weights are to be considered). This is where the OMOE plot comes in. As shown in Figure 4-4, the overall weighted MOE scores – one for each of the five systems – are plotted against both production and total cost,

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<sup>14</sup>Systems 3-5 have two vehicle types. For each parameter, the input for the first type is listed on the top row, and the input for the second type is on the second row.

System Definition Parameters	S1	S2	S3	S4	S5
Number of vehicle types	1	1	2	2	2
Host-system comms method	RF-Satellite	RF-Satellite	RF-Satellite	RF-Satellite	RF-Satellite
Reporting frequency	Periodic	Periodic	Continuous	Continuous	Continuous
System navigation fix method	GPS - surface	GPS - surface	GPS - link	GPS - link	GPS - link
Contact position error threshold (yards)	30	30	10	10	10
Reliability/redundancy level	High	High	High	High	High
Battery recharge method	Not required	Not required	Not required	Not required	Not required
Delivery method	Air	Air	Air	Air	Air
Recovery method	Surface	Surface	Surface	Surface	Surface
Vehicle Types	Hunter	Mini-hunter	Guide Mini-hunter	Guide Mini-hunter	Guide Hunter
Number of vehicles, each type	2	4	1 2	1 3	2 4
Surfacing requirement?	1	1	0	0	0
Sonar suite	ALS-21, SS-12	ALS-12, SS-12	None ALS-12, SS-12	None ALS-12, SS-12	None ALS-21, SS-12
Identification sensors	ID-MED	ID-MED	None ID-MED	None ID-MED	None ID-MED
Navigation suite	INS+DVS+GPS	INS+DVS+GPS	DR+DVS+GPS DR+DVS+tracker	DR+DVS+GPS DR+DVS+tracker	DR+DVS+GPS DR+DVS+tracker
Communication suite	RF	RF	RF Acoustic modem	RF Acoustic modem	RF Acoustic modem
Computer/processor	GC+K+S	GC+K+S	GC+S GC	GC+S GC	GC+S GC
Battery type	Li-Poly	Li-Poly	Li-Poly	Li-Poly	Li-Poly

Table 4.6: Case Two System Definition Inputs

Tactical Parameters	S1	S2	S3	S4	S5
Search velocity (knots)	4	4	4	4	4
Transit velocity (knots)	6	6	6	6	6
Vehicle Altitude (feet from bottom)	50	50	300 50	300 50	300 50
Search width, A (yards) [ALS / SS]	400 / 160	200 / 160	N/A 200 / 160	N/A 200 / 160	N/A 400 / 160
Probability of detection/classification, B [ALS / SS]	0.5 / 0.85	0.4 / 0.85	N/A 0.4 / 0.85	N/A 0.4 / 0.85	N/A 0.5 / 0.85
Probability identification	0.9	0.8	0.8	0.8	0.9
False contact density (per sqnm)	1.0	1.5	1.5	1.5	1.0
Navigation accuracy (% DT)	0.05	0.05	0.05	0.05	0.05
Track keeping accuracy (yards)	10	10	20	20	20

Table 4.7: Case Two Tactical Parameter Inputs

Sub-MOE	S1	S2	S3	S4	S5
Eff. Area Coverage Rate (sqnm/hr)	0.32	0.35	0.26	0.39	0.98
Percent Search	0.939	0.901	0.901	0.901	0.933
Localization Accuracy (yds)	15.00	15.00	5.00	5.00	5.00
Lift Requirement (sqft)	42.88	38.38	23.71	31.61	27.00
Host Requirement	1.00	1.00	1.00	1.00	1.00
Reporting Frequency	0.70	0.70	1.00	1.00	1.00
Data Type	1.00	1.00	1.00	1.00	1.00
Deployment Phase	0.30	0.30	0.30	0.30	0.30
Mission Phase	0.00	0.00	0.00	0.00	0.00
Recovery Phase	1.00	1.00	1.00	1.00	1.00
Costs					
Production (\$)	452,121	290,348	234,043	240,595	882,654
Research and Development (\$)	492,792	739,018	1,371,346	1,261,144	629,390
Total System Cost (\$)	944,913	1,029,366	1,605,389	1,501,739	1,512,044

Table 4.8: Case Two Results

providing a compact indication of the relative cost-effectiveness of each system.

Unfortunately, the OMOE method is not so ideal as to provide a definitive answer regarding which system is "the best". The decision-maker must determine the level of effectiveness that they are willing to pay for. The decision is further complicated by the presence of two different costs, one or the other of which may be more important for some reason. These cost-related preferences are not captured in the OMOE vs. Cost plots, nor are a number of other factors that could influence the decision. Still, the OMOE approach greatly simplifies the problem for the decision-maker, enabling them to apply judgement and reasoning in consideration of any remaining factors in order to reach a decision or conclusion.

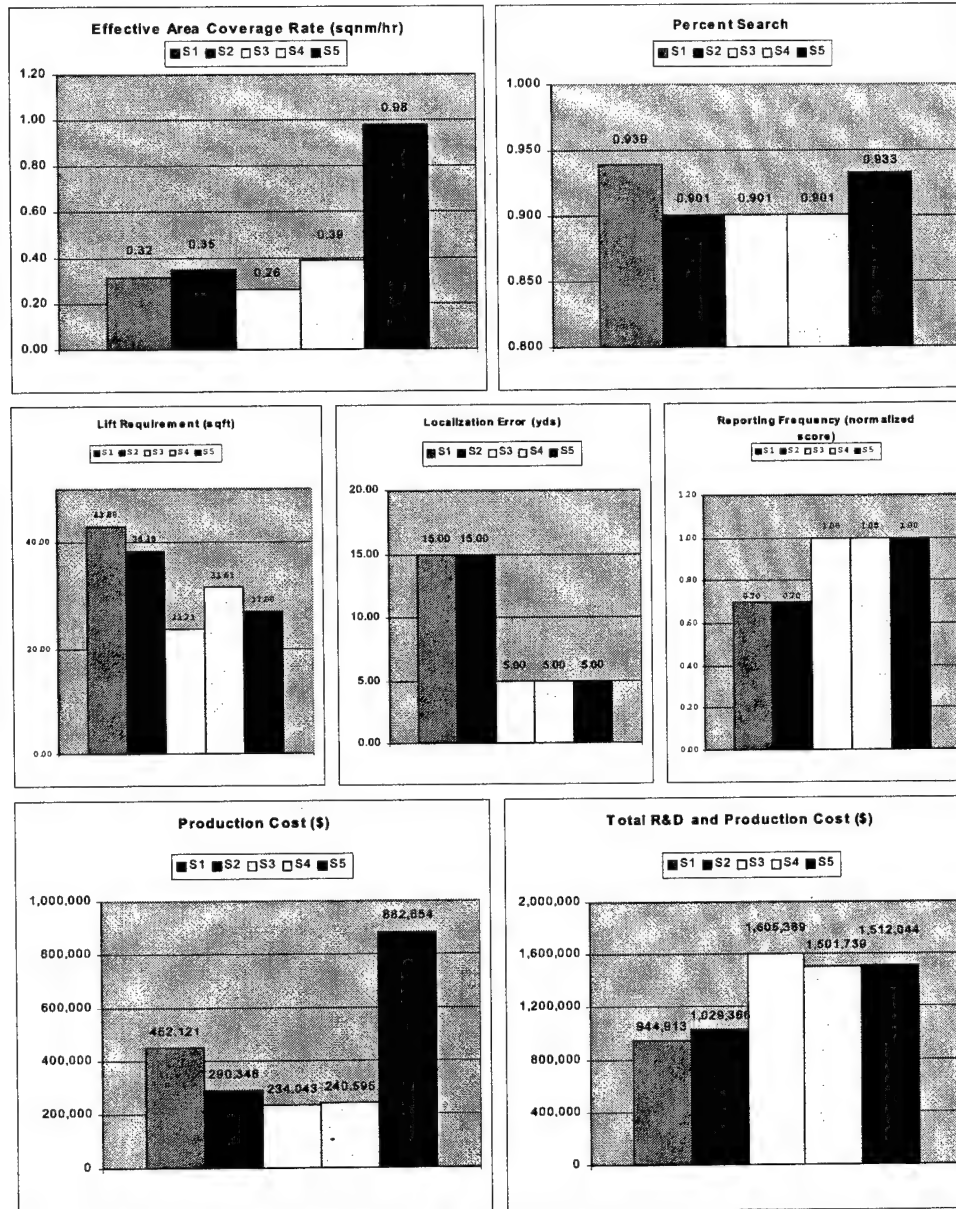


Figure 4-3: Comparison of Select Parameters for Case Two



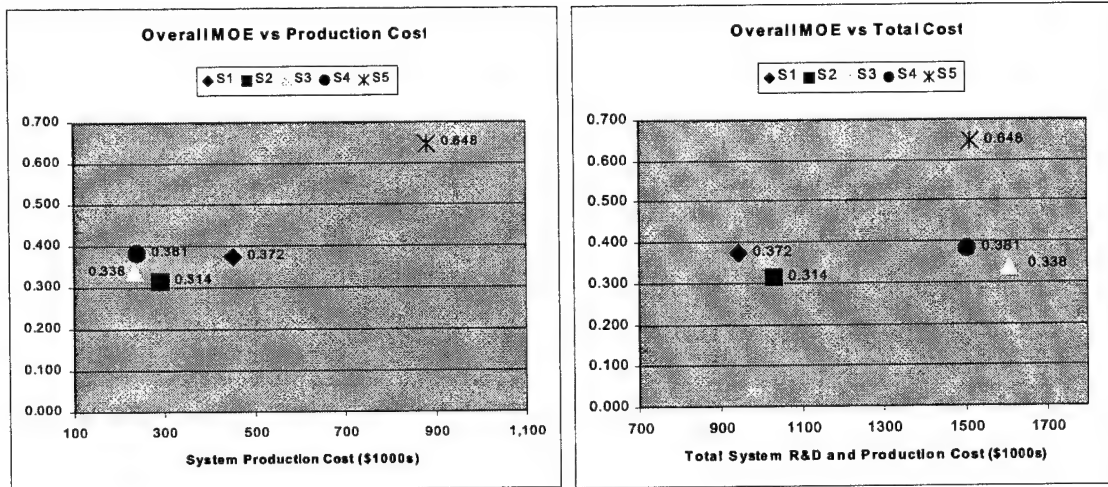


Figure 4-4: OMOE vs. Cost Plot for Case Two

## Chapter 5

# Conclusion

### 5.1 Summary of Work

The main objective of this thesis was to develop an analytical framework for the evaluation of advanced search concepts for multiple-AUV MCM. Supporting objectives called for identifying suitable metrics for evaluating multi-AUV MCM systems, defining and constructing the evaluation framework, and demonstrating its functionality and usefulness. The pursuit and attainment of these objectives led to the following “deliverables”:

- A recommended approach and associated methodology for evaluating unmanned/autonomous MCM systems, including multiple-AUV MCM systems.
- An effectiveness model, for measuring the degree to which a set of mission objectives is satisfied according to the preference structure of the warfighter.
- A system model, for transforming user-specified system requirements into a feasible design that is described by numeric values representing physical characteristics and performance.

The evaluation approach uses MOP and MOE, and the relationships between them, to describe a series of systems in terms of physical/performance characteristics and then to translate those characteristics into numeric values reflecting the mission-effectiveness of the systems. The mission-derived MOE are organized into a hierarchy and weighted, using AHP techniques, according to the warfighter’s preferences for a given scenario. Utility functions, modeling, and

simulation provide alternative means of relating these MOE to the system MOP. Implementation of this approach involves two computer-based models: the Effectiveness Model and the System Model.

The Effectiveness Model contains five MOE and eleven subordinate MOE which are intended to collectively portray the overall mission-effectiveness of any MCM system, but are especially geared toward unmanned/autonomous systems. Additionally, the model is meant to facilitate evaluation and comparison of MCM systems for all types of operations, including minehunting and mine clearance. Despite the intentions, the MOE selected may not be perfectly suitable for representing the present or future mission. A formal decomposition of the mission need by a panel of experts (using a QFD or similar technique) might reveal a different set of MOE. The Effectiveness Model can easily accommodate such replacements and modifications.

The System Model provides the environment in which candidate AUV MCM systems are defined and characterized. Whereas the Effectiveness Model applies generally, the System Model handles a limited range of AUV concepts. The acceptable range of *configurations* is fairly broad, including single- and multiple-AUV concepts with various mixes of sensors, navigation packages, communications gear, batteries, etc. The more significant limits have to do with *operational tactics* and *system behavior*, and are summarized as follows. MCM operations are confined to minehunting – detection through identification, but not clearance. A system is assumed to operate as a cohesive unit, except that individual vehicles may conduct minor excursions for mine prosecution and/or navigation and communication. The time required for these excursions is added to the mission time. The search pattern is restricted to progressive runs along parallel, uniformly-spaced tracks (lawnmower pattern) in a rectangular search area.

## 5.2 Applications and Future Work

The models developed for this thesis are not, themselves, meant to be used for comprehensive evaluation of multi-AUV MCM system concepts. Instead, it is the framework – the approach and its associated methodology – that was developed with this intention in mind. The Effectiveness Model and System Model developed here serve mainly to demonstrate the approach.

Two core applications for the evaluation framework were stated in Section 1.3. The first

application relates to AUV MCM system design and procurement decisions. The second application has to do with operational employment of a given system, assuming it already exists. For both applications, the evaluation framework helps to guide exploration of the vast trade-space associated with AUV MCM system concepts, with the ultimate goal being to identify the most effective design, configuration, or employment alternative as weighed against some cost(s), monetary or otherwise. In the design/procurement case, the framework provides a means of *designing to mission-effectiveness*, rather than optimizing the design to a set of performance specifications. This is a very powerful approach because it enlightens the designers, allowing them to observe and understand the impact of engineering decisions on the ultimate usefulness of the end product. By gaining this insight early in the design process, costly re-work, due to uninformed decisions and/or changes in the mission requirements, can be minimized. Regarding the employment application, the framework offers an opportunity to explore a much larger field of operational paradigms than would be examined during the design process. This may include assessing different system configurations (formed by mixing and matching re-configurable vehicles and sub-systems) and altering tactical parameters (e.g. speed, search pattern, contact prosecution algorithms) under a variety of scenarios.

A significant milestone for the evaluation of multi-AUV systems, for any mission, will be the development of a high-resolution, high-fidelity modeling/simulation environment in which a broad range of system concepts can be consistently and accurately evaluated in terms of mission-effectiveness and cost. The Effectiveness Model and System Model represent a step in this direction, but much work remains. In particular, the limitations of the System Model should be addressed. While a "static" analytical model appears to be sufficient for describing most of the physical characteristics of a multi-AUV system, and perhaps the basic aspects of individual vehicle performance, simulation may be preferable for addressing the more complex and time-dependent issues associated with tactical and operation employment. For example, a simulator could replicate exotic search algorithms that enable the multi-AUV system to change tactics in-stride, say, in response to changes in bottom clutter density. Simulation capability may also be used to *augment* a static model. In the case of the System Model, the sensing and/or navigation performance of multi-AUV systems could be provided by a simulator designed for that specific purpose, thus relieving the user of this burden and allowing more unusual system concepts

to be explored. High-fidelity performance simulators for critical areas (sensing, navigation, communication, etc.) will be essential to the implementation of a comprehensive multi-AUV MCM system evaluation framework.

While improvements in the framework's technical capabilities are important, more critical areas for future work relate to the types of analyses that can be performed and the nature/presentation of the information provided by the framework. For example, the Evaluation Model supports high-level, effectiveness-based comparison of any number of system concepts, but lacks the internal relationships and consistency checks necessary for detailed sensitivity analyses. Incorporating the capability to adjust individual system parameters and immediately observe the impact on mission-effectiveness over a range of inputs would significantly enhance the power of the evaluation framework.

### **5.3 Closing**

This thesis represents more than the individual effort of the author. Many people graciously contributed to this work, providing technical information, expert advice, general guidance, and just plain old support. Perhaps the most rewarding part of this experience has been the fascinating dialog that resulted from interacting with members of, and contributors to, the Navy's mine warfare community. It is the author's hope that both the process and the final product serve to benefit the community and the persons associated with it.

## Appendix A

# AUV MCM System Evaluation Model Technical Information

The Evaluation Model template resides in three distinct Mathcad files. One file is dedicated to the Effectiveness Model (Appendix C); the other two files contain the System Model (Appendix B). The AUV Design Module is separate from the Input and Mission Planning Modules so that multiple AUV types can each be modeled in a unique file. Imbedded in the System Model is an Excel file that contains a user interface sheet (part of the Input Module) and a series of databases for AUV sub-component characteristics (see Appendix D).

The Mathcad files are connected through “reference links”, allowing information to flow from the Input and Mission Planning Modules to both the AUV Design Module and the Effectiveness, as illustrated in Figure A-1. *Each reference link must be manually updated if the reference filename changes.* Similarly, the three output (file write) components at the end of the Effectiveness Model should also be updated so that the new output files are created with the desired filenames. It is recommended that the output components be disabled before the new Effectiveness Model file is created in order to avoid overwriting other output files.

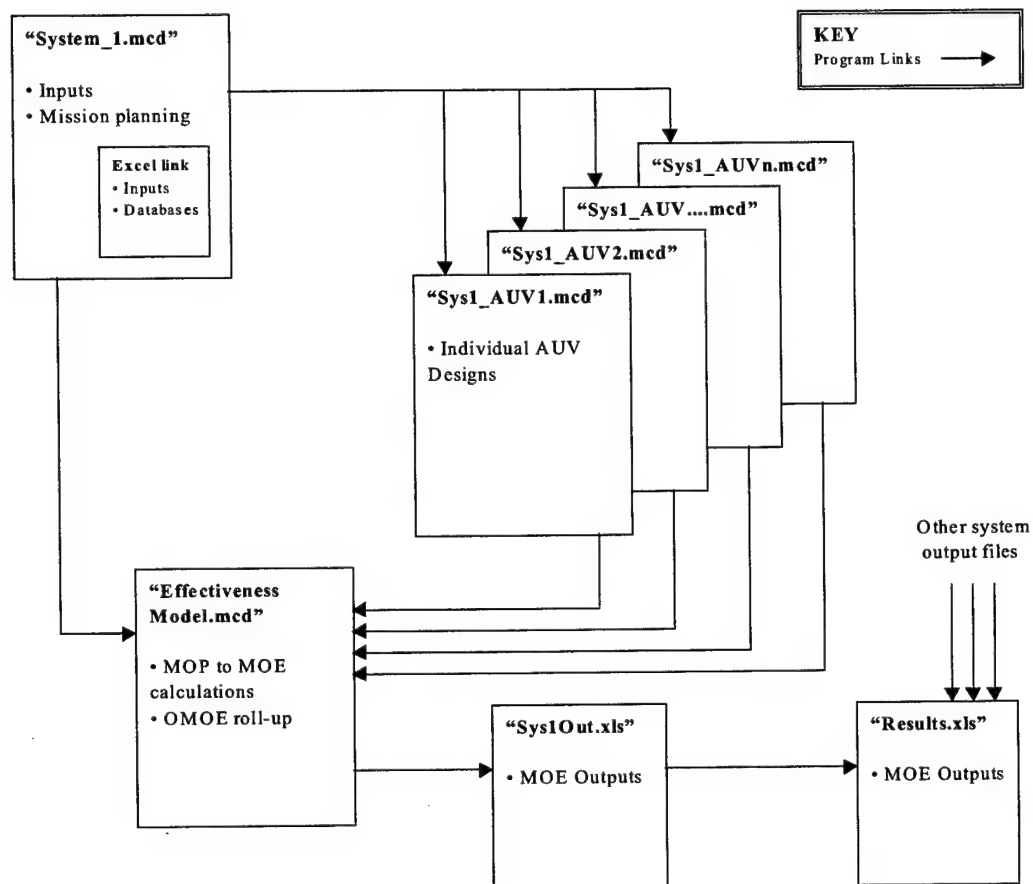


Figure A-1: Evaluation Model File Structure

# Appendix B

## System Model

### SYSTEM MODEL

#### Model Description

The System Model is the starting point for an evaluation problem. It has two main purposes:

- (1) To provide an environment in which to design/configure a notional AUV system
- (2) To determine the system MOP required as input to the Effectiveness Model

Three modules make up the System Model:

- INPUT MODULE: Scenario and tactical parameters are entered in the Mathcad worksheet; system-level and vehicle/payload entries are made in an Excel worksheet through a link. The Excel sheet contains databases with AUV sub-system weight, volume, and power data.
- MISSION PLANNING MODULE: Calculates total mission time required to achieve Percent Search objective, as well as the actual (achieved) Percent Search (almost always greater than the objective).
- AUV DESIGN MODULE: This module resides in a separate file in order to accommodate the design of multiple AUV types.

#### Constants

$$\text{dB} := 10 \log(\text{weber} \cdot \text{m}^{-2} \cdot 10^{-12} \cdot \text{weber}^{-1} \cdot \text{m}^2)$$

$$\text{nm} := 2025 \text{ yd}$$

$$\text{knt} := \frac{\text{nm}}{1 \cdot \text{hr}}$$



# I. MISSION AND SYSTEM INPUTS

## A. Scenario Parameters

### 1. Mission Objectives

#### Minehunting Objective:

Given as "Percent Search" achieved through minehunting for detection, classification, and up through identification. Enter fractional values as illustrated in guide table at right.

Mission Type	Typical Objective
Exploratory first-look	xx
Basic reconnaissance	xx
Detailed mapping	xx

$P_{\text{search\_desired}} := 0.94$

#### Search area dimensions:

$L_{\text{searcharea}} := 3\text{nm}$

$W_{\text{searcharea}} := 4000\text{yd}$

#### Distance from point of entry to search area:

Specify delivery/recovery methods (e.g. air, sub, surf) through Excel link below.

$d_{\text{ingress}} := 1\text{nm}$

#### Distance from search area to recovery point:

$d_{\text{egress}} := 5\text{nm}$

### 2. Environment

#### Bottom Type:

Bottom Type	Number	Design
Gravel	4	
Sand	9	

$BT := 4$

#### Average Water Depth:

$d_{\text{avg}} := 400\text{ft}$

### 3. Mine Threat

#### Estimated number of mines in search area:

$NM := 25$

#### Fraction of undetectable mines:

Zero entry is best for comparisons, and is appropriate if the individual sonar detection probabilities (B values) account for undetectable mines. Entering a value here implies that a certain fraction of mines are undetectable by ALL of the sensors in the system.

$\mu := 0$

#### Mine target strength:

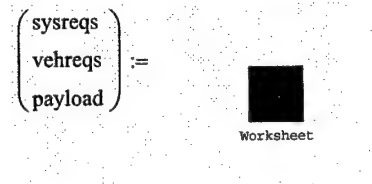
This parameter is used only as a reference for Sonar Performance Parameter entries (Section I.C.3).

$\gamma := -30\text{dB}$

## B. System Definition

### 1. Excel Input Link

Double click on the icon. Enter inputs in yellow-shaded areas of interface worksheet inside Excel. Use database sheets to guide input. When finished, save and close the link. Click once on the icon and press F9 to update Mathcad with the new info.



## System-Level Requirements

Item	Selection	Comments/Legend
Number of vehicle types	2	Selection must agree with number of entries in "Vehicle Requirements" section
Host-system comms method	RF-SAT	AM=acoustic modem, RF-LOS=radio freq via line of sight, RF-SAT=radio freq via satellite or aircraft, NR=not required
Reporting frequency	PRD	CONT=continuous, PRD=periodic, NR=not required <b>Note:</b> enter achievable reporting frequency based on comms method and opportunity to report (e.g. surface to transmit RF, host within AM range, etc.)
System navigation fix method	GPS-SURF	GPS-SURF=GPS by surfacing, GPS-LINK=constant GPS (e.g. buoys or antenna), LBL=Long Baseline or other array, NOFIX=DR only <b>Note:</b> enter method for system, regardless of which vehicles are involved in actual position fixing
Contact position error threshold (yds)	30	Maximum acceptable distance between actual and reported contact positions. <b>Note:</b> set value to reflect the achievable threshold using fix method prescribed above
Reliability/redundancy	LOW	LOW=system requires an in-theater support platform during search phase, HIGH=system does not require a support platform in theater during search phase or is expendable
Battery Recharge method	NR	HOST=vehicles rely on host platform for battery recharge; DOCK=battery recharge via in-water docking stations or equivalent system; NR=not required (i.e. endurance is greater than mission time)
Delivery method for clandestine ops	AIR	SUB=submarine, AIR=aircraft, SURF=surface ship <b>Note:</b> same for all vehicles in system
Recovery method for clandestine ops	SURF	SUB=submarine, AIR=aircraft, SURF=surface ship <b>Note:</b> same for all vehicles in system

## Vehicle Requirements and Payload

Item	Units	1	2	3	4	Comments/Legend
Type/Role	--	guide	hunter	0	0	Choose differentiating name
Number of vehicles (this type)	--	1	2	0	0	
Surfacing requirement toggle	--	1	0	0	0	1 if yes, 0 if no
Max Length	ft	20	20	0	0	Ensure consistency with system reqs; zero if no limit
Max Diameter	in	21	21	0	0	Ensure consistency with system reqs; zero if no limit
Max Deadweight	lb	500	500	0	0	Ensure consistency with system reqs; zero if no limit
Sonar #1	--	ALS-21	SS-12	0	0	Use exact desig from database
Sonar #2	--	0	0	0	0	Use exact desig from database
Sonar #3	--	0	0	0	0	Use exact desig from database
ID Sensor	--	0	ID-LOW	0	0	Use exact desig from database
Nav Suite	--	INS-DVS-GPS	DR-DVS-ABR	0	0	Use exact desig from database
Comms	--	AM+RF	AM	0	0	Use exact desig from database
Computer/Processor	--	GC+K+S	GC	0	0	Use exact desig from database
Battery Type	--	Ag-Zn	Ag-Zn	0	0	Use exact desig from database
Sensor Suite Weight	lb	20.3	7.2	0.0	0.0	NOTE: check these lookup formulas if databases changed
Sensor Suite Volume	cuin	924.0	718.4	0.0	0.0	
Sensor Suite Power	watt	139.4	41.0	0.0	0.0	assume 100% duty cycle
Nav Suite Weight	lb	10.0	20.6	0.0	0.0	
Nav Suite Volume	cuin	146.5	719.8	0.0	0.0	
Nav Suite Power	watt	23.0	24.3	0.0	0.0	assume 100% duty cycle
Comms Suite Weight	lb	2.5	1.5	0.0	0.0	
Comms Suite Volume	cuin	61.7	37.0	0.0	0.0	
Comms Suite Power	watt	12.0	9.0	0.0	0.0	assume 100% duty cycle
Computer/Processor Weight	lb	4.0	2.0	0.0	0.0	
Computer/Processor Volume	cuin	300.0	75.0	0.0	0.0	
Computer/Processor Power	watt	40.0	15.0	0.0	0.0	assume 100% duty cycle
Battery Specific Energy	watt-hr/lb	40.8	40.8	0.0	0.0	
Battery Energy Density	watt-hr/cuft	5097.0	5097.0	0.0	0.0	
Battery Weight to Volume Ratio	lb/cuft	124.9	124.9	0.0	0.0	Not used

User must ensure that payload components' diameters correspond with max vehicle diameter

## 2. System Requirements

From spreadsheet link:

sysreqs =	"Number of vehicle types"	2
	"Host-system comms method"	"RF-SAT"
	"Reporting frequency"	"PRD"
	"System navigation fix method"	"GPS-SURF"
	"Contact position error threshold (yds)"	30
	"Reliability/redundancy"	"LOW"
	"Battery Recharge method"	"NR"
	"Delivery method for clandestine ops"	"AIR"
	"Recovery method for clandestine ops"	"SURF"

Variable assignment:

numtype := sysreqs 1,2	numtype = 2
comm_method := sysreqs 2,2	comm_method = "RF-SAT"
report_freq := sysreqs 3,2	report_freq = "PRD"
fix_method := sysreqs 4,2	fix_method = "GPS-SURF"
max_pos_error := sysreqs 5,2.yd	max_pos_error = 30yd
reliability := sysreqs 6,2	reliability = "LOW"
recharge := sysreqs 7,2	recharge = "NR"
cland_deliv := sysreqs 8,2	cland_deliv = "AIR"
cland_recov := sysreqs 9,2	cland_recov = "SURF"

## 3. Vehicle Requirements

From spreadsheet link:

vehreqs =	"Type/Role"	"--"	"guide"	"hunter"	0	0
	"Number of vehicles (this type)"	"--"	1	2	0	0
	"Surfacing requirement toggle"	"--"	1	0	0	0
	"Max Length"	"ft"	20	20	0	0
	"Max Diameter"	"in"	21	21	0	0
	"Max Deadweight"	"lb"	500	500	0	0

Variable assignment:

**submatrix(A,ir,jr,ic,jc)** returns the matrix consisting of rows **ir** through **jr** and columns **ic** through **jc** of array **A**.

$\text{type} := \text{if}(\text{numtype} = 1, \text{vehreqs}_{1, \text{numtype}+2}, \text{submatrix}(\text{vehreqs}, 1, 1, 3, \text{numtype} + 2))$        $\text{type} = (\text{"guide"} \quad \text{"hunter"})$   
 $\text{numveh} := \text{if}(\text{numtype} = 1, \text{vehreqs}_{2, \text{numtype}+2}, \text{submatrix}(\text{vehreqs}, 2, 2, 3, \text{numtype} + 2))$        $\text{numveh} = (1 \quad 2)$   
 $\text{surf\_req} := \text{if}(\text{numtype} = 1, \text{vehreqs}_{3, \text{numtype}+2}, \text{submatrix}(\text{vehreqs}, 3, 3, 3, \text{numtype} + 2))$        $\text{surf\_req} = (1 \quad 0)$   
 $\text{Lmax} := \text{if}(\text{numtype} = 1, \text{vehreqs}_{4, \text{numtype}+2}, \text{submatrix}(\text{vehreqs}, 4, 4, 3, \text{numtype} + 2)) \cdot \text{ft}$        $\text{Lmax} = (20 \quad 20) \text{ ft}$   
 $\text{Dmax} := \text{if}(\text{numtype} = 1, \text{vehreqs}_{5, \text{numtype}+2}, \text{submatrix}(\text{vehreqs}, 5, 5, 3, \text{numtype} + 2)) \cdot \text{in}$        $\text{Dmax} = (21 \quad 21) \text{ in}$   
 $\text{Wmax} := \text{if}(\text{numtype} = 1, \text{vehreqs}_{6, \text{numtype}+2}, \text{submatrix}(\text{vehreqs}, 6, 6, 3, \text{numtype} + 2)) \cdot \text{lb}$        $\text{Wmax} = (500 \quad 500) \text{ lb}$

#### 4. Vehicle Payload

From spreadsheet link:

	1	2	3	4
1	"Sonar #1"	"_"	"ALS-21"	"SS-12"
2	"Sonar #2"	"_"	0	0
3	"Sonar #3"	"_"	0	0
4	"ID Sensor"	"_"	0	"ID-LOW"
5	"Nav Suite"	"_"	S-DVS-GPS"	R-DVS-ABR"
6	"Comms"	"_"	"AM+RF"	"AM"
7	r/Processor"	"_"	"GC+K+S"	"GC"
8	attery Type"	"_"	"Ag-Zn"	"Ag-Zn"
9	uite Weight"	"lb"	20.3	7.175
10	uite Volume"	"cuin"	924	718.38
payload = 11	Suite Power"	"watt"	139.4	41
12	uite Weight"	"lb"	9.969	20.55
13	uite Volume"	"cuin"	146.51	719.753
14	Suite Power"	"watt"	22.95	24.25
15	uite Weight"	"lb"	2.5	1.5
16	uite Volume"	"cuin"	61.714	37.029
17	Suite Power"	"watt"	12	9
18	ssor Weight"	"lb"	4	2
19	ssor Volume"	"cuin"	300	75
20	ssor Power"	"watt"	40	15
21	cific Energy"	"watt-hr/lb"	40.824	40.824
22	rgy Density"	"watt-hr/cuft"	$5.097 \cdot 10^3$	$5.097 \cdot 10^3$

### Variable assignment:

$$\begin{aligned}
 W_{\text{sensors}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{9, \text{numtype}+2}, \text{submatrix}(\text{payload}, 9, 9, 3, \text{numtype} + 2)) \cdot \text{lb} & W_{\text{sensors}} &= (20.3 \ 7.175) \text{ lb} \\
 V_{\text{sensors}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{10, \text{numtype}+2}, \text{submatrix}(\text{payload}, 10, 10, 3, \text{numtype} + 2)) \cdot \text{in}^3 & V_{\text{sensors}} &= (924 \ 718.4) \text{ in}^3 \\
 P_{\text{sensors}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{11, \text{numtype}+2}, \text{submatrix}(\text{payload}, 11, 11, 3, \text{numtype} + 2)) \cdot \text{watt} & P_{\text{sensors}} &= (139.4 \ 41) \text{ watt} \\
 W_{\text{nav}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{12, \text{numtype}+2}, \text{submatrix}(\text{payload}, 12, 12, 3, \text{numtype} + 2)) \cdot \text{lb} & W_{\text{nav}} &= (9.969 \ 20.55) \text{ lb} \\
 V_{\text{nav}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{13, \text{numtype}+2}, \text{submatrix}(\text{payload}, 13, 13, 3, \text{numtype} + 2)) \cdot \text{in}^3 & V_{\text{nav}} &= (146.5 \ 719.8) \text{ in}^3 \\
 P_{\text{nav}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{14, \text{numtype}+2}, \text{submatrix}(\text{payload}, 14, 14, 3, \text{numtype} + 2)) \cdot \text{watt} & P_{\text{nav}} &= (22.95 \ 24.25) \text{ watt} \\
 W_{\text{comms}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{15, \text{numtype}+2}, \text{submatrix}(\text{payload}, 15, 15, 3, \text{numtype} + 2)) \cdot \text{lb} & W_{\text{comms}} &= (2.5 \ 1.5) \text{ lb} \\
 V_{\text{comms}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{16, \text{numtype}+2}, \text{submatrix}(\text{payload}, 16, 16, 3, \text{numtype} + 2)) \cdot \text{in}^3 & V_{\text{comms}} &= (61.7 \ 37) \text{ in}^3 \\
 P_{\text{comms}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{17, \text{numtype}+2}, \text{submatrix}(\text{payload}, 17, 17, 3, \text{numtype} + 2)) \cdot \text{watt} & P_{\text{comms}} &= (12 \ 9) \text{ watt} \\
 W_{\text{computer}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{18, \text{numtype}+2}, \text{submatrix}(\text{payload}, 18, 18, 3, \text{numtype} + 2)) \cdot \text{lb} & W_{\text{computer}} &= (4 \ 2) \text{ lb} \\
 V_{\text{computer}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{19, \text{numtype}+2}, \text{submatrix}(\text{payload}, 19, 19, 3, \text{numtype} + 2)) \cdot \text{in}^3 & V_{\text{computer}} &= (300 \ 75) \text{ in}^3 \\
 P_{\text{computer}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{20, \text{numtype}+2}, \text{submatrix}(\text{payload}, 20, 20, 3, \text{numtype} + 2)) \cdot \text{watt} & P_{\text{computer}} &= (40 \ 15) \text{ watt} \\
 \gamma_{\text{battery}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{21, \text{numtype}+2}, \text{submatrix}(\text{payload}, 21, 21, 3, \text{numtype} + 2)) \frac{\text{watt} \cdot \text{hr}}{\text{lb}} & \gamma_{\text{battery}} &= (40.824 \ 40.824) \frac{\text{watt} \cdot \text{hr}}{\text{lb}} \\
 \rho_{\text{battery}} &:= \text{if}(\text{numtype} = 1, \text{payload}_{22, \text{numtype}+2}, \text{submatrix}(\text{payload}, 22, 22, 3, \text{numtype} + 2)) \frac{\text{watt} \cdot \text{hr}}{\text{ft}^3} & \rho_{\text{battery}} &= (5097 \ 5097) \frac{\text{watt} \cdot \text{hr}}{\text{ft}^3}
 \end{aligned}$$

## C. Tactical Parameters

### 1. Speed and Endurance

Note: This version of the model assumes the following:

- (1) all vehicles in the system move together at the same speed
- (2) all vehicles must have enough endurance to complete mission

Search Speed:

$$V_{\text{search}} := 6 \text{ knt}$$

Average system search speed; individual vehicles may travel at different speeds.

Transit Speed:

$$V_{\text{transit}} := 10 \text{ knt}$$

Vehicles assumed to transit en masse

Prosecution speed:

$$V_{\text{prosecute}} := V_{\text{transit}}$$

Speed at which ID-tasked vehicle(s) prosecute mine-like contacts; this can be adjusted to "even out" vehicle mission times (computed at the very end of this model). Should not go above  $V_{\text{transit}}$ .

### 2. Search Parameters

Vehicle Altitudes:

$$\text{ALT} := (350 \ 100 \ 0 \ 0) \text{ ft}$$

ALT must not exceed avg depth.

$$d_{\text{avg}} = 400 \text{ ft}$$

### 3. Sonar Performance Parameters

#### Directions:

1. Enter sonar performance parameters FOR EACH SONAR in terms of the characteristic search width "A" and characteristic probability of detection/classification "B". [These simplified values can be derived from a "probability of detection as a function of lateral distance", or P(y) curve; Reference PEO(MIW) INST 3370 for definition of these parameters.]

2. The following reference parameters are provided for looking pre-determined up the "A" and "B" values (reference MCM Future Systems Study for some notional ALS, SAS, and SS sonar values):

vehicle altitude (ALT)      search speed (Vs)  
bottom type (BT)            target strength ( $\gamma$ )  
water depth ( $d_{avg}$ )

3. For cooperative multi-AUV operations, the A and B values can be adjusted to reflect the "effective" performance due to more efficient search tactics and/or increases in search probabilities due to communication between vehicles, data fusion, multi-static operations, and so forth.

Reference Parameters:       $Sonar\_Suite := submatrix(payload, 1, 3, 1, 6)$

$$Sonar\_Suite = \begin{pmatrix} "Sonar \#1" & "-" & "ALS-21" & "SS-12" & 0 & 0 \\ "Sonar \#2" & "-" & 0 & 0 & 0 & 0 \\ "Sonar \#3" & "-" & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$V_{search} = 6 \text{ knt}$$

$$ALT = (350 \ 100 \ 0 \ 0) \text{ ft}$$

$$BT = 4$$

$$d_{avg} = 400 \text{ ft}$$

$$\gamma = -30 \text{ dB}$$

Sonar Parameter Entry:

Vehicle types

Characteristic Search Width

$$A := \begin{pmatrix} 588 & 588 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \text{ yd} \quad \text{Sonar types}$$

Characteristic Probability of Detection/Classification

$$B := \begin{pmatrix} 0.8756 & 0.95 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Probability of identifying a mine as a mine

$$P_{imm} := .95$$

False contact density for identification

$$\lambda_{imm} := 1 \text{ nm}^{-2}$$

- Must be less than total mine density

$$\frac{NM}{L_{searcharea} W_{searcharea}} = 4.219 \text{ nm}^{-2}$$

### 4. Navigation Performance Parameters

Navigation "growth error" (for system):      %DT := 0.05

Standard deviation of track keeping:       $\sigma := (5 \ 10 \ 0 \ 0) \text{ yd}$

$$\sigma := \begin{pmatrix} \sigma_{1,1} & \sigma_{1,2} & \sigma_{1,3} & \sigma_{1,4} \\ \sigma_{1,1} & \sigma_{1,2} & \sigma_{1,3} & \sigma_{1,4} \\ \sigma_{1,1} & \sigma_{1,2} & \sigma_{1,3} & \sigma_{1,4} \end{pmatrix}$$

## II. MCM MISSION PLANNING MODULE

Based on Uniform Clearance (UCPLN)  
Theory (ref. PEO(MIW) INST 3370)

### A. Probability Parameters

#### 1. Non-dimensionalization

$$A_{nd} := \frac{A}{yd} \quad \sigma_{nd} := \frac{\sigma}{yd}$$

$$D_{track} := \frac{W_{searcharea}}{N}$$

$$D_{track.nd} := \frac{D_{track}}{yd}$$

Note: N = number of tracks, a global variable defined at Section II.C.

#### 2. MCM Efficiency Coefficient

Y is the coefficient of MCM efficiency. In simple terms it is the payoff from covering the area in an orderly manner, rather than randomly. As randomness decreases (B increasing or  $\sigma$  decreasing) Y increases. This equation was derived by Dr. R.K. Reber many years ago by averaging the probability of clearance between two parallel tracks in the central part of the channel where there were no edge effects; i.e., the channel edges were far enough away to the left and right that extending the width of the channel would have no effect.

$$Y := \begin{cases} \text{for } i \in 1..rows(A) \\ \text{for } j \in 1..cols(A) \\ y_{i,j} \leftarrow \frac{2 \cdot \sigma_{nd,i,j}}{A_{nd,i,j} \cdot B_{i,j}} \cdot \int_0^{\infty} \ln \left[ 1 - B_{i,j} \cdot \left( \text{cnorm} \left( u + \frac{A_{nd,i,j}}{2 \cdot \sigma_{nd,i,j}} \right) - \text{cnorm} \left( u - \frac{A_{nd,i,j}}{2 \cdot \sigma_{nd,i,j}} \right) \right) \right] du \text{ if } B_{i,j} \neq 0 \\ y \end{cases}$$

$$Y = (2.357 \ 3.066)$$

#### 3. "M" Term

M represents a combination of the level of coverage (the search width, A, times the number of runs, J, divided by the track spacing, D) and the success of detection/classification over the area covered (probability, B).

$$M := \begin{cases} \text{for } i \in 1..rows(A) \\ \text{for } j \in 1..cols(A) \\ m_{i,j} \leftarrow \frac{J \cdot A_{nd,i,j} \cdot B_{i,j}}{D_{track.nd}} \text{ if } B_{i,j} \neq 0 \\ m \end{cases}$$

$$M = (0.901 \ 0.978)$$

## B. Percent Search Calculations

### 1. Percent Search - Each Sensor

$$P_{\text{each\_sensor}} := \begin{cases} \text{for } i \in 1.. \text{rows}(Y) \\ \text{for } j \in 1.. \text{cols}(Y) \\ p_{i,j} \leftarrow (1 - \mu) P_{\text{imm}} \cdot [1 - e^{-1(M_{i,j} \cdot Y_{i,j})}] \text{ if } Y_{i,j} \neq 0 \\ p \end{cases}$$

$$P_{\text{each\_sensor}} = (0.836 \ 0.903)$$

### 2. Percent Search - System Total

$$i := 1.. \text{rows}(P_{\text{each\_sensor}}) \quad j := 1.. \text{cols}(P_{\text{each\_sensor}})$$

$$P_{\text{search\_no\_mu}} := 1 - \left[ \prod_j \left[ \prod_i (1 - P_{\text{each\_sensor}_{i,j}}) \right] \right]$$

$$P_{\text{search\_no\_mu}} = 0.984$$

$$P_{\text{search}} := (1 - \mu) \cdot P_{\text{search\_no\_mu}}$$

$$P_{\text{search}} = 0.984$$

## C. Required Search Parameter Values (to achieve desired Percent Search)

Adjust to get desired  $P_{\text{search}}$

Required number of tracks:

$$N \equiv 7$$

$$P_{\text{search}} = 0.984$$

$$P_{\text{search\_desired}} = 0.94$$

Number of runs per track:

$$J \equiv 1$$

Track spacing:

Ensure  $D_{\text{track}}$  is less than the smallest non-zero A value

$$D_{\text{track}} = 571.429 \text{yd}$$

$$A = \begin{pmatrix} 588 & 588 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \text{yd}$$

## D. Mission Time

### 1. Transit Time

Transit distance:

$$d_{\text{transit}} := d_{\text{ingress}} + d_{\text{egress}}$$

$$d_{\text{transit}} = 6 \text{nm}$$

Transit time:

$$T_{\text{transit}} := \frac{d_{\text{transit}}}{V_{\text{transit}}}$$

$$T_{\text{transit}} = 0.6 \text{hr}$$



## 2. Search Time

Total track distance:	$d_{\text{track\_runs}} := L_{\text{searcharea}} \cdot N \cdot J$	$d_{\text{track\_runs}} = 21 \text{ nm}$
Total turns distance:	$d_{\text{turns}} := [(N \cdot J) - 1] \cdot D_{\text{track}} \cdot 1.1$ assumes 10% "excess" on each turn	$d_{\text{turns}} = 1.862 \text{ nm}$
Search distance (incl turns):	$d_{\text{search}} := d_{\text{track\_runs}} + d_{\text{turns}}$	$d_{\text{search}} = 22.9 \text{ nm}$
Search time:	$T_{\text{search}} := \frac{d_{\text{search}}}{V_{\text{search}}}$	$T_{\text{search}} = 3.81 \text{ hr}$

## 3. Comm/Nav Excursion Time

System common parameters:

Nav/comm reqs (from input):  
 $\text{fix\_method} = \text{"GPS-SURF"}$   
 $\text{report\_freq} = \text{"PRD"}$

"No fix" interval: applicable to systems with fixing capability  
 $d_{\text{no\_fix}} := \frac{\text{max\_pos\_error}}{\%DT}$   
 $d_{\text{no\_fix}} = 600 \text{ yd}$

Frequency/number of fixes:  
 $N_{\text{fixes}} := \frac{d_{\text{track\_runs}}}{d_{\text{no\_fix}}}$   
 $N_{\text{fixes}} = 70.875$

Vehicle parameters (arrays indicate values for specific vehicle types):

Vehicle surfacing rqmts (from input):  
 $\text{surf\_req} = (1 \ 0)$  1 = surf req, 0 = no surf req

Number of surfacing evolutions:  
 $N_{\text{surf}} := N_{\text{fixes}}$  assumes number of fixes dictated by nav requirements

Time on surface (typical value):  
 $T_{\text{xmit\_rcv}} := 0 \text{ sec}$  (enter zero if negligible)

Ascent/descent rate (typical value):  
 $\text{ascent\_descent\_rate} := 200 \frac{\text{ft}}{\text{min}}$

Distance to surface:  
 $\text{alt} := \text{if}(\text{numtype} = 1, \text{ALT}_{1,1}, \text{submatrix}(\text{ALT}, 1, 1, 1, \text{numtype}))$   
 $\text{alt} = (350 \ 100) \text{ ft}$

$d_{\text{surface}} := d_{\text{avg}} - \text{alt}$   $d_{\text{surface}} = (50 \ 300) \text{ ft}$

Ascent/descent time:  
 $T_{\text{ascent\_descent}} := \frac{2d_{\text{surface}}}{\text{ascent\_descent\_rate}}$   $T_{\text{ascent\_descent}} = (0.5 \ 3) \text{ min}$

Excursion time summary:  $T_{\text{excursion}} :=$  for  $i \in 1.. \text{numtype}$   
 (for each vehicle) 
$$\begin{cases} x_{1,i} \leftarrow \text{surf\_req}_{1,i} \cdot N_{\text{surf}}(T_{\text{ascent\_descent}_{1,i}} + T_{\text{xmit\_recv}}) & \text{if numtype} > 1 \\ x \leftarrow \text{surf\_req} \cdot N_{\text{surf}}(T_{\text{ascent\_descent}} + T_{\text{xmit\_recv}}) & \text{otherwise} \end{cases}$$
  
 $x$

$$T_{\text{excursion}} = (0.591 \ 0) \text{ hr}$$

Check against search time:

$$T_{\text{search}} = 3.81 \text{ hr}$$

If excursion time is unreasonable, vehicle altitude and/or number of fixes may need to be adjusted. If necessary, override with estimate based on search time?

#### 4. Prosecution Time (for identification)

$$NM = 25$$

$$\lambda_{\text{imm}} = 1 \text{ nm}^{-2}$$

Number of ID attempts: 
$$NIA := \left[ NM \cdot (1 - \mu) + \lambda_{\text{imm}} \cdot W_{\text{searcharea}} L_{\text{searcharea}} \right] \cdot \frac{P_{\text{each\_sensor}_i}}{P_{\text{imm}}}$$

$$NIA = 27.227$$

Identification time (per attempt): 
$$T_{\text{mine\_ID}} := \frac{0.5 D_{\text{track}} \cdot 2}{V_{\text{prosecute}}} \quad T_{\text{mine\_ID}} = 1.693 \text{ min}$$

Assumptions (state if formula changed):

1. Typical prosecution will involve one vehicle transiting about half the track distance, including both horizontal and vertical distance to the contact from the search track.
2. Multiply by 2 for return to place in formation.
3. Prosecution speed set in Section I.C.1; can be adjusted to match overall system mission time (see sub-section 5 below).

Total identification time: 
$$T_{\text{prosecute}} := NIA \cdot T_{\text{mine\_ID}} \quad T_{\text{prosecute}} = 0.768 \text{ hr}$$

Prosecution time: 
$$ID\_Sensors := \text{submatrix}(\text{payload}, 4, 4, 3, 6)$$

(for each vehicle) 
$$ID\_Sensors = (0 \text{ "ID-LOW"} \ 0 \ 0)$$

$$T_{\text{prosecute}} := \begin{cases} \text{for } i \in 1.. \text{numtype} \\ x_{1,i} \leftarrow T_{\text{prosecute}} & \text{if } ID\_Sensors_{1,i} \neq 0 \\ x \end{cases} \quad T_{\text{prosecute}} = (0 \ 0.768) \text{ hr}$$

## 5. Mission and Endurance Time

Estimated vehicle mission times:

$$T_{\text{mission\_veh\_est}} := T_{\text{search}} + T_{\text{transit}} + T_{\text{excursion}} + T_{\text{prosecute}}$$

$$T_{\text{mission\_veh\_est}} = (5.001 \ 5.179) \text{ hr}$$

Review these times to ensure they fit the system CONOPS. For example, if the system is intended to search as a unit, then the mission times for each vehicle type should be close. In reality, vehicles with special assignments (like surfacing or prosecuting) may speed up or slow down to regain position. These cases may be somewhat accounted for by adjusting the prosecution speed for the ID vehicle(s) (Section I.C.1). Remember that this will effect the amount of energy required by that/those vehicles as computed in the AUV Design Module.

Total mission time for system:

$$T_{\text{mission}} := \max(T_{\text{mission\_veh\_est}})$$

$$T_{\text{mission}} = 5.179 \text{ hr}$$

Required vehicle endurance time (same for each type):

$$T_{\text{endurance\_req}} := 1.5 \cdot \max(T_{\text{mission\_veh\_est}})$$

$$T_{\text{endurance\_req}} = 7.768 \text{ hr}$$

Include margin

## III. AUV DESIGN MODULE

Individual AUVs are designed in separate .mcd files that reference the System Model for inputs.

# AUV DESIGN MODULE

## Model Description

The AUV Design Module is a sub-components of the System Model, and is used to design each vehicle type. The modeling approach is derived from the MIT 13A SSN Math Model, a submarine design tool based largely on parametric studies performed by CAPT Harry Jackson, USN (Ret).

## Constants

Caution: constant are carried into this model through the reference links as well; be sure to avoid conflicts by check System Model "Constants" section.

$$\begin{array}{lll} l_{\text{ton}} := 2240 \text{ lb} & v_{\text{SW}} := 1.281710^{-5} \cdot \frac{\text{ft}^2}{\text{sec}} & \\ f_{\text{Curve}} \equiv 1.176 & \rho_{\text{SW}} := 64.0 \frac{\text{lb}}{\text{ft}^3} & \rho_{\text{SW}}^{-1} = 35 \frac{\text{ft}^3}{l_{\text{ton}}} \end{array}$$

## I. INPUTS

UPDATE REFERENCE LINK PATH -- DELETE LINK AND  
INSERT NEW ONE (USE "RELATIVE LINK" OPTION)

Enter number corresponding to vehicle  
being modeled in this worksheet (i.e.  
for first column of numbers, enter "1")

Reference: C:\My Documents\MIT\Thesis\Modeling\Master\System Model - Master.mcd(R)

v := 1

$$W_{\text{sensors}} = (20.3 \ 7.175) \text{ lb}$$

$$W_{\text{sensors}} := W_{\text{sensors}_{1,v}}$$

$$V_{\text{sensors}} = (924 \ 718.4) \text{ in}^3$$

$$V_{\text{sensors}} := V_{\text{sensors}_{1,v}}$$

$$P_{\text{sensors}} = (139.4 \ 41) \text{ watt}$$

$$P_{\text{sensors}} := P_{\text{sensors}_{1,v}}$$

$$W_{\text{nav}} = (9.969 \ 20.55) \text{ lb}$$

$$W_{\text{nav}} := W_{\text{nav}_{1,v}}$$

$$V_{\text{nav}} = (146.5 \ 719.8) \text{ in}^3$$

$$V_{\text{nav}} := V_{\text{nav}_{1,v}}$$

$$P_{\text{nav}} = (22.95 \ 24.25) \text{ watt}$$

$$P_{\text{nav}} := P_{\text{nav}_{1,v}}$$

$$W_{\text{comms}} = (2.5 \ 1.5) \text{ lb}$$

$$W_{\text{comms}} := W_{\text{comms}_{1,v}}$$

$$V_{\text{comms}} = (61.7 \ 37) \text{ in}^3$$

$$V_{\text{comms}} := V_{\text{comms}_{1,v}}$$

$$P_{\text{comms}} = (12 \ 9) \text{ watt}$$

$$P_{\text{comms}} := P_{\text{comms}_{1,v}}$$

$$W_{\text{computer}} = (4 \ 2) \text{ lb}$$

$$W_{\text{computer}} := W_{\text{computer}_{1,v}}$$

$$V_{\text{computer}} = (300 \ 75) \text{ in}^3$$

$$V_{\text{computer}} := V_{\text{computer}_{1,v}}$$

$$P_{\text{computer}} = (40 \ 15) \text{ watt}$$

$$P_{\text{computer}} := P_{\text{computer}_{1,v}}$$

$$\gamma_{\text{battery}} = (40.824 \ 40.824) \frac{\text{watt} \cdot \text{hr}}{\text{lb}}$$

$$\gamma_{\text{battery}} := \gamma_{\text{battery}_{1,v}}$$

$$\rho_{\text{battery}} = (5097 \ 5097) \frac{\text{watt} \cdot \text{hr}}{\text{ft}^3}$$

$$\rho_{\text{battery}} := \rho_{\text{battery}_{1,v}}$$

$$T_{\text{excursion}} = (0.591 \ 0) \text{ hr}$$

$$T_{\text{excursion}} := T_{\text{excursion}_{1,v}}$$

$$T_{\text{prosecute}} = (0 \ 0.768) \text{ hr}$$

$$T_{\text{prosecute}} := T_{\text{prosecute}_{1,v}}$$

## A. Power Requirements

### 1. Initial Power Estimates

Mission time (estimated in System Model):

$$T_{\text{endurance\_req}} = 7.768 \text{ hr}$$

Hotel power (based on payload input):

$$P_{\text{HotelReq}} := P_{\text{sensors}} + P_{\text{nav}} + P_{\text{comms}} + P_{\text{computer}}$$

$$P_{\text{HotelReq}} = 214.35 \text{ watt}$$

$$E_{\text{HotelReq}} := P_{\text{HotelReq}} \cdot T_{\text{endurance\_req}}$$

$$E_{\text{HotelReq}} = 1.665 \text{ kW} \cdot \text{hr}$$

## Propulsion power estimate:

For initial propulsion power estimate, enter estimate of vehicle diameter.

- First, enter a minimum diameter based on any components that constrain it. This model is set up for sonars of certain minimum diameters, so the sonar suite is shown below. The user can add any other components.
- Max diameter is provided by the system requirements.

Set min diameter:

$$D_{\min} := 21 \text{ in}$$

$$\text{Sonar\_Suite}^{(v+2)} = \begin{pmatrix} \text{"ALS-21"} \\ 0 \\ 0 \end{pmatrix}$$

Recall max diameter:

$$D_{\max, v} := 21 \text{ in}$$

$$D_{\max} := \text{if}(\text{numtype} > 1, D_{\max, v}, D_{\max})$$

Enter estimated vehicle diameter based on min and max above. LOD and the actual D are set as global variables in Section III.A.

Estimated/desired diameter:

$$D_{\text{est}} := 21 \text{ in}$$

$$D_{\min} = 21 \text{ in}$$

$$D_{\max} = 21 \text{ in}$$

$$\text{LOD} D_{\text{est}} = 10.5 \text{ ft}$$

Equation provides brake power estimate for torpedo-shaped underwater vehicles (Ref. Hildebrand, NUWC). Global variables D and LOD set in Section III.A.

$$P_{\text{Prop\_est}}(V) := \frac{1}{0.6} \cdot 1.2173 \cdot 10^{-8} \cdot \left( \frac{\text{LOD} D_{\text{est}}}{\text{mm}} \right)^{0.75} \cdot \left( \frac{D_{\text{est}}}{\text{mm}} \right)^{1.25} \cdot \left( \frac{V}{\text{m} \cdot \text{sec}^{-1}} \right)^{2.86} \cdot \text{kW} \quad P_{\text{Prop\_est}}(V_{\text{search}}) = 0.555 \text{ kW}$$

$$E_{\text{Prop\_est}} := P_{\text{Prop\_est}}(V_{\text{search}}) \cdot T_{\text{endurance\_req}}$$

Assumes average mission velocity equal to  $V_{\text{search}}$

$$E_{\text{Prop\_est}} = 4.315 \text{ kW} \cdot \text{hr}$$

## 2. Propulsion Power

Motor selection:

$$P_{\text{PropPeak\_est}} := P_{\text{Prop\_est}}(V_{\text{transit}})$$

Used to guide motor selection; use max sustained speed (e.g. transit speed, burst speed, etc.)

Est. peak propulsion pwr:

$$P_{\text{PropPeak\_est}} = 3.21 \text{ hp}$$

$$P_{\text{MotorRating}} := 3 \text{ hp}$$

Select motor power rating using peak propulsion power estimate (left). Check  $V_{\text{max}}$  in Section V.G to ensure it is sufficient (i.e. greater than all required speeds).

Max vehicle diameter:

$$D_{\max} = 21 \text{ in}$$

$$D_{\text{motor}} := 10 \text{ in}$$

Enter motor diameter corresponding to power rating. Must be less than max vehicle diameter.

Power Volume Density:

$$\rho_{\text{prop}} := 3500 \frac{\text{watt}}{\text{ft}^3}$$

Enter propulsion plant volume density (include support systems and components)

Power Weight Density:

$$\gamma_{\text{prop}} := 40 \frac{\text{watt}}{\text{lb}}$$

Enter propulsion plant weight density (include support systems and components)

Checks (from MCM WG model):

$$\rho := \frac{0.072 \text{ft}^3}{0.28 \text{kW}} \quad \rho = 0.257 \frac{\text{ft}^3}{\text{kW}} \quad \frac{1}{\rho} = 3889 \frac{\text{watt}}{\text{ft}^3}$$

$$\gamma := \frac{7.6 \text{lb}}{0.28 \text{kW}} \quad \gamma = 27.143 \frac{\text{lb}}{\text{kW}} \quad \frac{1}{\gamma} = 36.842 \frac{\text{watt}}{\text{lb}}$$

### 3. Energy Source

Estimated required energy:  $E_{\text{Mission\_est}} := E_{\text{HotelReq}} + E_{\text{Prop\_est}} \quad E_{\text{Mission\_est}} = 5.98 \text{kW} \cdot \text{hr}$

Installed energy:  $E_{\text{Installed}} = 9.5 \text{kW} \cdot \text{hr}$

Battery specific energy:  $\gamma_{\text{battery}} = 40.82 \frac{\text{watt} \cdot \text{hr}}{\text{lb}}$

Battery energy density:  $\rho_{\text{battery}} = 5097 \frac{\text{watt} \cdot \text{hr}}{\text{ft}^3}$

## B. Payload Weight and Volume Inputs

### 1. Payload Weights

$$W_{\text{sensors}} = 20.3 \text{lb}$$

$$W_{\text{nav}} = 10 \text{lb}$$

$$W_{\text{comms}} = 2.5 \text{lb}$$

$$W_{\text{computer}} = 4 \text{lb}$$

### 2. Payload Volumes

$$V_{\text{sensors}} = 0.535 \text{ft}^3$$

$$V_{\text{nav}} = 0.085 \text{ft}^3$$

$$V_{\text{comms}} = 0.036 \text{ft}^3$$

$$V_{\text{computer}} = 0.174 \text{ft}^3$$

## C. Other Inputs

### Internal Structure and Arrangement

Internal Structure Factor	SF := 0.2	Internal structure volume as fraction of payload volume
Volume Packing Factor (Dry Hull)	PFdry := 1.0	Applied to dry volume subtotal to account for component spacing, free floods, growth margin, etc.
Volume Packing Factor (Wet Hull)	PFwet := 0.1	Applied to wet volume subtotal to account for component spacing, free floods, growth margin, etc.
Ballast Factor	BF := 0.1	Reserved ballast volume as fraction of pressure hull volume; assumed to be for "hard" variable ballast tanks.

## **II. VOLUME REQUIRED**

### **A. Preliminary Volumes Calculations**

$$V_{\text{battery}} := \frac{E_{\text{Installed}}}{\rho_{\text{battery}}}$$

$$V_{\text{battery}} = 1.864\text{ft}^3$$

$$V_{\text{propulsion}} := \frac{P_{\text{MotorRating}}}{\rho_{\text{prop}}}$$

$$V_{\text{propulsion}} = 0.639\text{ft}^3$$

### **B. Dry (Pressure) Hull Volumes**

Payload and other vehicle components for pressure hull:

$$V_{\text{nav}} = 0.085\text{ft}^3$$

Select appropriate components from Sections I.B.2 and II.A.  
Ensure following equations include appropriate items.

$$V_{\text{computer}} = 0.174\text{ft}^3$$

$$V_{\text{battery}} = 1.864\text{ft}^3$$

$$V_{\text{propulsion}} = 0.639\text{ft}^3$$


---

Standard pressure hull items:

$$V_{\text{dry\_internal\_structure}} := \text{SF} \cdot (V_{\text{nav}} + V_{\text{computer}} + V_{\text{battery}} + V_{\text{propulsion}})$$

$$V_{\text{dry\_internal\_structure}} = 0.552\text{ft}^3$$


---

Pressure Hull Volume:

$$V_{\text{PH}} := (1 + \text{PF}_{\text{dry}}) \cdot (V_{\text{nav}} + V_{\text{computer}} + V_{\text{battery}} + V_{\text{propulsion}} + V_{\text{dry\_internal\_structure}})$$

$$V_{\text{PH}} = 6.627\text{ft}^3$$

### **C. Wet Hull Volumes**

Payload and other vehicle components for wet hull:

$$V_{\text{sensors}} = 0.535\text{ft}^3$$

Select appropriate components from Sections I.B.2 and II.A.  
Ensure following equations include appropriate items.

$$V_{\text{comms}} = 0.036\text{ft}^3$$


---

Standard wet hull items:

$$V_{\text{wet\_internal\_structure}} := \text{SF} \cdot (V_{\text{sensors}} + V_{\text{comms}})$$

$$V_{\text{wet\_internal\_structure}} = 0.114\text{ft}^3$$

$$V_{\text{ballast\_tank}} := \text{BF} \cdot V_{\text{PH}}$$

$$V_{\text{ballast\_tank}} = 0.663\text{ft}^3$$


---

Wet Hull Volume:

$$V_{\text{WH}} := (1 + \text{PF}_{\text{wet}}) \cdot (V_{\text{sensors}} + V_{\text{comms}} + V_{\text{wet\_internal\_structure}} + V_{\text{ballast\_tank}})$$

$$V_{\text{WH}} = 1.482\text{ft}^3$$



#### D. Everbuoyant Volume

$$V_{eb} := V_{PH} + V_{sensors} + V_{comms} + V_{wet\_internal\_structure} + V_{ballast\_tank}$$

$$V_{eb} = 7.975 \text{ft}^3$$

#### E. Submerged Volume and Displacement

$$V_s := V_{eb}$$

Assumes "hard" ballast tanks, i.e. no change in displacement for submergence -- only weight is changed.

$$V_s = 7.975 \text{ft}^3$$

$$\Delta_s := V_s \cdot \rho_{SW}$$

$$\Delta_s = 510.373 \text{lb}$$

#### F. Required Envelope Volume and Displacement

$$V_{envr} := V_{PH} + V_{WH}$$

Appendages (i.e. control surfaces, antennas, etc.) are not included.

$$V_{envr} = 8.109 \text{ft}^3$$

$$\Delta_{envr} := V_{envr} \cdot \rho_{SW}$$

$$\Delta_{envr} = 518.996 \text{lb}$$

### III. ENVELOPE VOLUME AVAILABLE

#### A. Spin a Hull:

Based on the volume requirements calculated in Section II, select L, D, length of parallel mid-body, and forward & aft shape factors.

Select D:  $D \equiv 21 \text{in}$

Constraints:

Based on user entries in AUV System Model and component sizes

Select L/D:  $LOD \equiv 6$  Optimum = 6

$$D_{min} := \max(D_{min}, D_{motor})$$

$$D_{min} = 21 \text{in}$$

$$L := LOD \cdot D$$

$$L_{max\_v} = 20 \text{ft}$$

$$D_{max} = 1.75 \text{ft}$$

$$L_{max} := \text{if}(\text{numtype} > 1, L_{max\_v}, L_{max})$$

$$L_{max} = 20 \text{ft}$$

$$D_{check} := \text{if}[(D \leq D_{max} \wedge D \geq D_{min}), "OK", "RESIZE"]$$

Dimensions:

$$D = 21 \text{in}$$

$$L = 10.5 \text{ft}$$

$$L_{check} := \text{if}(L \leq L_{max}, "OK", "RESIZE")$$

Checks:

$$D_{check} = "OK"$$

$$L_{check} = "OK"$$

Use following section to adjust nose, tail, and parallel midbody lengths.

Entrance:  $\eta_f := 2.25$  Optimum = 2.25

Run:  $\eta_a := 2.75$  Optimum = 2.75

Nose length:  $L_f := 2.4 \cdot D$  Optimum =  $2.4 \cdot D$

$$L_f = 4.2 \text{ft}$$

Tail length:  $L_a := \left(6 - \frac{L_f}{D}\right) \cdot D$

$$L_a = 6.3 \text{ft}$$

Parallel midbody:  $L_{pmb} := (LOD - 6) \cdot D$

$$L_{pmb} = 0 \text{ft}$$

$$\text{Length} := L_f + L_a + L_{pmb}$$

$$\text{Length} = 10.5 \text{ft}$$

## B. Volume Calculations to Support Arrangement:

1. Entrance:  $L_f = 4.2\text{ft}$

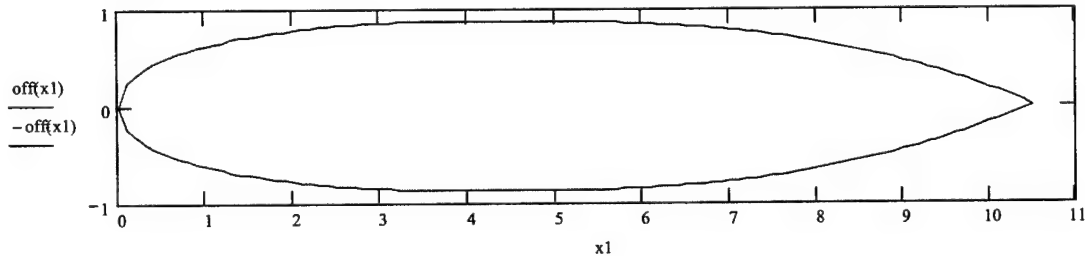
$$y_{f1}(x1) := \left[ 1 - \left( \frac{L_f - x1}{L_f} \right)^{\eta_f} \right]^{\frac{1}{\eta_f}} \cdot \frac{D}{2} \quad x1 := 0\text{-ft}, .1\text{-ft} \dots L_f + L_{pmb}$$

$$\text{off}(x1) := \text{if} \left( x1 < L_f, y_{f1}(x1), \frac{D}{2} \right)$$

2. Run:  $L_a = 6.3\text{ft}$   $x1 := 0\text{-ft}, .1\text{-ft} \dots L$

$$y_a(x1) := \left[ 1 - \left[ \frac{x1 - (L_f + L_{pmb})}{L_a} \right]^{\eta_a} \right] \cdot \frac{D}{2}$$

3. Total Ship:  $\text{offt}(x1) := \text{if}(x1 \leq L_f + L_{pmb}, \text{off}(x1), y_a(x1))$



4. Total Ship Volume

$$V_{\text{tot}} := \int_{0\text{-ft}}^L \text{offt}(x1)^2 \cdot \pi \, dx1 \quad V_{\text{tot}} = 16.602\text{ft}^3 \quad V_{\text{enva}} := V_{\text{tot}}$$

$$\Delta_{\text{enva}} := \rho_{\text{SW}} \cdot V_{\text{tot}} \quad \Delta_{\text{enva}} = 1062.553\text{b}$$

5. Tail Cone angle (measured from the axis of rotation to the tangent at the stern). Greater than 18 degrees probably considered a full stern.

$$\text{asin} \left[ \frac{\frac{D}{L_a}}{1 + \left[ \frac{1}{2} \cdot \left( \frac{D}{L_a} \right)^2 \right]} \right] = 15.814\text{deg}$$

6. Total Prismatic Coefficient

$$C_p := \frac{V_{\text{tot}}}{\pi \cdot \left( \frac{D}{2} \right)^2 \cdot L} \quad C_p = 0.657$$

7. Forward Prismatic and Wetted Surface Area Coefficients:

$$C_{pf} := \frac{\int_{0.8}^{2.4 \cdot D} \text{offt}(x1)^2 \cdot \pi \, dx1}{\pi \cdot \frac{D^3}{4} \cdot 2.4} \quad C_{pf} = 0.7127 \quad C_{wsf} := \frac{\int_{0.8}^{2.4 \cdot D} 2 \cdot \text{offt}(x1) \cdot \pi \, dx1}{\pi \cdot D^2 \cdot 2.4} \quad C_{wsf} = 0.8189$$

8. After Prismatic and Wetted Surface Area Coefficients:

$$C_{pa} := \frac{\int_{(L-3.6 \cdot D)}^L \text{offt}(x1)^2 \cdot \pi \, dx1}{\pi \cdot \frac{D^3}{4} \cdot 3.6} \quad C_{pa} = 0.6205 \quad C_{wsa} := \frac{\int_{(L-3.6 \cdot D)}^L 2 \cdot \text{offt}(x1) \cdot \pi \, dx1}{\pi \cdot D^2 \cdot 3.6} \quad C_{wsa} = 0.7333$$

9. Available Envelope Displacement and Wetted Surface Area:

$$\begin{aligned} K1 &:= 6 - 2.4 C_{pf} - 3.6 C_{pa} & K1 &= 2.056 \\ K2 &:= 6 - 2.4 C_{wsf} - 3.6 C_{wsa} & K2 &= 1.395 \\ WS &:= \pi \cdot D^2 \cdot (LOD - K2) & WS &= 44.309 \text{ft}^2 \end{aligned}$$

10. Envelope Volume Balance.

Outboard volumes are not included in the hull sizing.

$$V_{envr} = 8.109 \text{ft}^3 \quad V_{enva} = 16.602 \text{ft}^3 \quad Err_v := \frac{V_{enva} - V_{envr}}{V_{envr}}$$

Ensure that available volume exceeds required volume. A +/- 1% error bound is preferred, but most AUVs will require excess volume to achieve required buoyancy:

$$Err_v = 1.047\%$$

If  $Err_v < 0$ , then available volume is too small, so increase envelope volume.

If  $Err_v > 0$ , then available volume is too large, so decrease envelope volume unless restricted by weight.

## IV. WEIGHT AND BUOYANCY

NOTE: This section not important if size of vehicle is known. The powering calcs are based on size, not weight. Cost is determined primarily from payload components (?).

### A. Weight Estimation

#### 1. Lightship Weight (excluding fixed ballast)

Traditional SWBS Groups	AUV Components	Group Number
Hull Structure	Structure, Mountings	1
Propulsion Plant	Motor, Propulsor, Shaft, Gears, Fins	2
Electrical Plant	Batteries, Wiring, Junctions	3
Command and Control	Controllers, Recorders	4
Auxiliary Systems	Ballast Equip, Hydraulics	5
Outfit and Furnishings	n/a	6
Mission Payload	Sensors, Navigation, Comms, Computer	7

Required envelope and submerged displacements (from above):  $\Delta_{env} = 1062.553\text{lb}$   $\Delta_s = 510.373\text{lb}$

Group 1 fraction of available envelope displacement:  $W_{1\text{frac}} := .15$

Group 2 weight fraction (from above):  $W_{2\text{frac}} := \gamma_{\text{prop}}^{-1}$

Group 3 weight fraction (from above):  $W_{3\text{frac}} := \gamma_{\text{battery}}^{-1}$

Group 4 fraction of submerged displacement:  $W_{4\text{frac}} := .01$

Group 5 fraction of submerged displacement:  $W_{5\text{frac}} := .02$

Group 6 fraction of submerged displacement:  $W_{6\text{frac}} := 0$

Group 7 (from spreadsheet):  $W_{7\text{est}} := W_{\text{sensors}} + W_{\text{nav}} + W_{\text{comms}} + W_{\text{computer}}$

	ESTIMATED VALUES	ACTUAL VALUES	Enter if known
$W_{1\text{est}} := W_{1\text{frac}} \cdot \Delta_{\text{env}}$	$W_{1\text{est}} = 159.383\text{lb}$	$W_1 := W_{1\text{est}}$	
$W_{2\text{est}} := W_{2\text{frac}} \cdot P_{\text{MotorRating}}$	$W_{2\text{est}} = 55.926\text{lb}$	$W_2 := W_{2\text{est}}$	
$W_{3\text{est}} := W_{3\text{frac}} \cdot E_{\text{Installed}}$	$W_{3\text{est}} = 232.706\text{lb}$	$W_3 := W_{3\text{est}}$	
$W_{4\text{est}} := W_{4\text{frac}} \cdot \Delta_s$	$W_{4\text{est}} = 5.104\text{lb}$	$W_4 := W_{4\text{est}}$	
$W_{5\text{est}} := W_{5\text{frac}} \cdot \Delta_s$	$W_{5\text{est}} = 10.207\text{lb}$	$W_5 := W_{5\text{est}}$	
$W_{6\text{est}} := W_{6\text{frac}} \cdot \Delta_s$	$W_{6\text{est}} = 0\text{lb}$	$W_6 := W_{6\text{est}}$	
	$W_{7\text{est}} = 36.769\text{lb}$	$W_7 := W_{7\text{est}}$	

Lightship weight (excl fixed ballast):  $W_{A1} := W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7$

Check:

$$W_{A1} = 500.095\text{lb}$$

$$W_{\text{max}} = (500 - 500)\text{lb}$$

## 2. Ballast Requirements

Positive Buoyancy as fraction of submerged displacement:  $B_{frac} := 0.01$

$$B_{pos} := B_{frac} \Delta_s$$

$$B_{pos} = 5.104 \text{ lb}$$

Weight-buoyancy balance to determine fixed ballast requirements:

$$W_{FB\_req} := \Delta_s - W_{A1} - B_{pos}$$

$$W_{FB\_req} = 5.174 \text{ lb}$$

Positive value indicates requirement for additional weight (e.g. lead ballast).

Negative value indicates requirement for added buoyancy (e.g. foam, bladder)

Lead requirement:

$$W_{lead} := \text{if}(W_{FB\_req} > 0, W_{FB\_req}, 0)$$

$$W_{lead} = 5.174 \text{ lb}$$

$$\rho_{pb} := 11.37 \frac{\text{gm}}{\text{cm}^3} \quad \rho_{pb} = 11370 \frac{\text{kg}}{\text{m}^3}$$

$$V_{lead} := \frac{W_{lead}}{\rho_{pb}}$$

$$V_{lead} = 0.007 \text{ ft}^3$$

Buoyant material requirement:

$$V_{foam} := \text{if}\left(W_{FB\_req} < 0, \frac{-W_{FB\_req}}{\rho_{SW}}, 0\right)$$

$$V_{foam} = 0 \text{ ft}^3$$

Assume weight of foam is negligible.

Fixed ballast volume:

$$V_{fb} := V_{lead} + V_{foam}$$

$$V_{fb} = 0.007 \text{ ft}^3$$

$$W_{fb} := W_{lead}$$

$$W_{fb} = 5.174 \text{ lb}$$

Volume check:

$$V_{fixed\_ballast\_avail} := V_{enva} - V_{envr}$$

$$V_{fixed\_ballast\_avail} = 8.493 \text{ ft}^3$$

$$V_{fb\_check} := \text{if}(V_{fixed\_ballast\_avail} \geq V_{fb}, \text{"OK"}, \text{"NOT OK"})$$

$$V_{fb\_check} = \text{"OK"}$$

Variable ballast volume:

Ballast tank volume (from above):

$$V_{ballast\_tank} = 0.663 \text{ ft}^3$$

$$V_{vb} := 0.9 \cdot V_{ballast\_tank}$$

$$V_{vb} = 0.596 \text{ ft}^3$$

$$W_{vb} := V_{vb} \cdot \rho_{SW}$$

$$W_{vb} = 38.173 \text{ lb}$$

Negative buoyancy check:

$$B_{neg} := B_{pos} - W_{vb}$$

$$B_{neg} = -33.07 \text{ lb}$$

$$B_{frac\_neg} := \frac{-B_{neg}}{\Delta_s}$$

$$B_{frac\_neg} = 0.065$$

$$B_{neg\_check} := \text{if}(B_{frac\_neg} > B_{frac}, \text{"OK"}, \text{"NOT OK"})$$

$$B_{neg\_check} = \text{"OK"}$$

## B. Weight Summary

$$W_{ls} := W_{A1} + W_{lead} \quad \Delta_A := W_{ls}$$

$$W_{ls} = 505.27 \text{ lb}$$

$$W_{fl} := W_{ls} + W_{vb}$$

$$W_{fl} = 543.443 \text{ lb}$$

## V. SPEED, POWER, AND RANGE

Speed range of interest:  $V := 0, .1, .15$

$$V_{\text{search}} = 6 \text{ knot}$$

$$V_{\text{transit}} = 10 \text{ knot}$$

Sections A through C present different methods of calculating the drag coefficient. User can select method in Section E.

### A. Drag Coefficient (Jackson Wetted Surface), $C_{D\_WET1}$

#### 1. Resistance calculation parameters:

Reynolds Number:  $R_N(V) := L \cdot \frac{V \cdot \text{knt}}{\nu_{SW}}$

Wetted Surface (previously calculated):  $WS = 44.309 \text{ ft}^2$

Correlation Allowance:  $C_a := .0004$

For ships, this is typically .0004. CAPT Jackson's notes indicate that  $C_a$  should be .0002 - .0015 for submarines.

#### 2. Frictional resistance coefficient:

$$C_f(V) := \frac{.075}{(\log(R_N(V)) - 2)^2}$$

#### 3. Residual drag coefficient:

The following equation for  $(C_f + C_r)/C_f$  was developed by Hoerner using the fact that the after end of the submarine has a large effect on the form coefficient (See Reference 1)

$$C_{ff} := 1 + 1.5 \left( \frac{D}{L_a} \right)^{1.5} + 7 \cdot \left( \frac{D}{L_a} \right)^3 + .002(C_p - .6) \quad C_{ff} = 1.37$$

$$C_r(V) := C_{ff} C_f(V) - C_f(V)$$

#### 4. Appendage drag coefficient:

Estimate appendage area as a fraction of wetted surface area and use 0.006 for appendage drag coef.

Check against alternative methods:

1. Rule of thumb for submarines is that the non-sail appendages have a  $A \cdot C_d$  ("App" below) value equal to approximately  $L \cdot D / 1000$ .
2. Percentage of total resistance coefficient w/out appendages.

$$f_{app} := 0.05 \quad C_{app} := .006$$

Compare to:

$$1. \quad App := \frac{L \cdot D}{1000} \quad App = 0.0184 \text{ ft}^2$$

$$C_{app} \cdot f_{app} \cdot WS = 0.0133 \text{ ft}^2$$

$$2. \quad C_{aff}(V) := WS \cdot (C_f(V) + C_r(V) + C_a)$$

$$C_{app10\%}(V) := 0.10 C_{aff}(V)$$

$$C_{app10\%}(10) = 0.0190 \text{ ft}^2$$

#### 5. Total drag coefficient:

$$C_{D\_WET1}(V) := C_a + C_f(V) + C_r(V) + C_{app} \cdot f_{app}$$

$$C_{D\_WET1} \left( \frac{V_{\text{search}}}{\text{knt}} \right) = 0.005$$

## B. Drag Coefficient (Hoerner Wetted Surface Method), $C_{D\_WET2}$

Bare hull drag coefficient:

$$C_{D\_BH\_WET2}(V) := C_F(V) \cdot \left[ (1) + 1.5 \cdot \left( \frac{D}{L} \right)^{1.5} + 7 \cdot \left( \frac{D}{L} \right)^3 \right] \quad C_{D\_BH\_WET2} \left( \frac{V_{search}}{knt} \right) = 0.004$$

## C. Drag Coefficient (Hoerner Frontal Area Method), $C_{D\_FRONT}$

Total drag coefficient (bare hull only):

$$C_{D\_BH\_FRONT}(V) := C_F(V) \cdot \left[ 3 \cdot \left( \frac{L}{D} \right) + 4.5 \cdot \left( \frac{D}{L} \right)^{0.5} + 21 \cdot \left( \frac{D}{L} \right)^2 \right] \quad C_{D\_BH\_FRONT} \left( \frac{V_{search}}{knt} \right) = 0.063$$

## D. Resistance

### 1. Jackson Wetted Surface Method

$$R_{T\_WET1}(V) := 0.5 \cdot \rho_{SW} \cdot WS \cdot C_{D\_WET1}(V) \cdot (V \cdot knt)^2 \quad R_{T\_WET1} \left( \frac{V_{search}}{knt} \right) = 22.345 \text{ lbf}$$

### 2. Hoerner Wetted Surface Method (with Jackson method for appendage drag)

Bare hull:

$$R_{BH\_WET2}(V) := 0.5 \cdot \rho_{SW} \cdot WS \cdot C_{D\_BH\_WET2}(V) \cdot (V \cdot knt)^2 \quad R_{BH\_WET2} \left( \frac{V_{search}}{knt} \right) = 15.888 \text{ lbf}$$

Appendage:

$$R_{APP}(V) := 0.5 \cdot \rho_{SW} \cdot C_{app} \cdot f_{app} \cdot WS \cdot (V \cdot knt)^2 \quad R_{APP} \left( \frac{V_{search}}{knt} \right) = 1.355 \text{ lbf}$$

Total:

$$R_{T\_WET2}(V) := R_{BH\_WET2}(V) + R_{APP}(V) \quad R_{T\_WET2} \left( \frac{V_{search}}{knt} \right) = 17.243 \text{ lbf}$$

### 3. Hoerner Frontal Area Surface Method (with Jackson method for appendage drag)

Bare hull:

$$R_{BH\_FRONT}(V) := 0.5 \cdot \rho_{SW} \cdot \frac{\pi \cdot D^2}{4} \cdot C_{D\_BH\_FRONT}(V) \cdot (V \cdot knt)^2 \quad R_{BH\_FRONT} \left( \frac{V_{search}}{knt} \right) = 15.524 \text{ lbf}$$

Appendage:

$$R_{APP}(V) := 0.5 \cdot \rho_{SW} \cdot C_{app} \cdot f_{app} \cdot WS \cdot (V \cdot knt)^2 \quad R_{APP} \left( \frac{V_{search}}{knt} \right) = 1.355 \text{ lbf}$$

Total:

$$R_{T\_FRONT}(V) := R_{BH\_FRONT}(V) + R_{APP}(V) \quad R_{T\_FRONT} \left( \frac{V_{search}}{knt} \right) = 16.88 \text{ lbf}$$

## E. Powering Requirements

Propulsive Coefficient:  $PC := 0.85$

Motor efficiency:  $\eta_{\text{motor}_V} := 0.85$   $V_{\text{eff}} := 10 \text{ knt}$  Enter efficiency and corresponding speed

$$\eta_{\text{motor}}(V) := \eta_{\text{motor}_V} \cdot (V \cdot \text{knt} \cdot V_{\text{eff}}^{-1})^7$$

Accounts for motor inefficiency at lower speeds.

Resistance calc method:  $R_T(V) := R_{T\_WET1}(V)$  Enter desired method from previous section.

Brake power (includes estimated PC and motor efficiency):

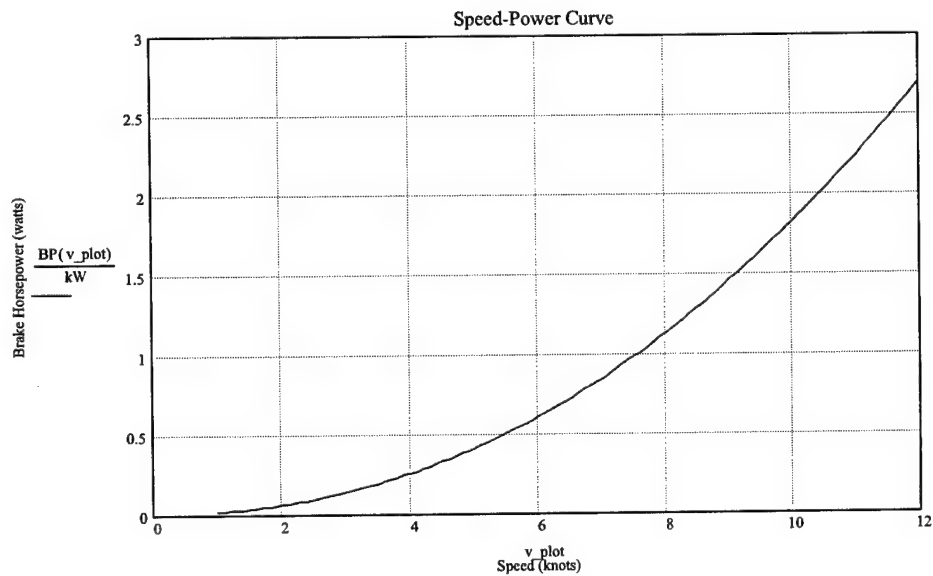
$$BP(V) := \frac{R_T(V) \cdot V \cdot \text{knt}}{\left(550 \frac{\text{ft} \cdot \text{lbf}}{\text{sec} \cdot \text{hp}}\right) \cdot PC \cdot \eta_{\text{motor}}(V)}$$

$V1 := 4, 6..10$

$BP(V1) =$	
0.254	kW
0.607	
1.127	
1.823	

## F. Powering Results

$v_{\text{plot}} := 1, 1.1..12$





### G. Maximum Speed (Submerged)

$a := 10$  (initial estimate for root finder)

$$P_{\text{MotorRating}} = 2237.051 \text{ watt}$$

$$V_{\text{max}} := \text{root}(BP(a) - P_{\text{MotorRating}}, a) \cdot \text{knt}$$

$$V_{\text{max}} = 10.995 \text{ knt}$$

$$V_{\text{search}} = 6 \text{ knt}$$

Re-select motor size to achieve maximum required speed (usually  $V_{\text{search}}$  or  $V_{\text{transit}}$ ).

$$V_{\text{transit}} = 10 \text{ knt}$$

### H. Optimum Speed (Submerged)

Optimum transit speed is that which uses one half the power of the hotel load:  $P_{\text{transit}} = 1/2 \cdot P_{\text{hotel}}$

$$BP_{\text{optimum}} := 0.5 P_{\text{HotelReq}}$$

$$BP_{\text{optimum}} = 107.175 \text{ watt}$$

Following formula determines the speed at which the desired (i.e. ideal) transit power is achieved:

$b := 10$  (initial estimate for root finder)

$$V_{\text{optimum}} := \text{root}(BP(a) - BP_{\text{optimum}}, a) \cdot \text{knt}$$

$$V_{\text{optimum}} = 2.669 \text{ knt}$$

For information only

### I. Energy Consumption and Endurance Calcs

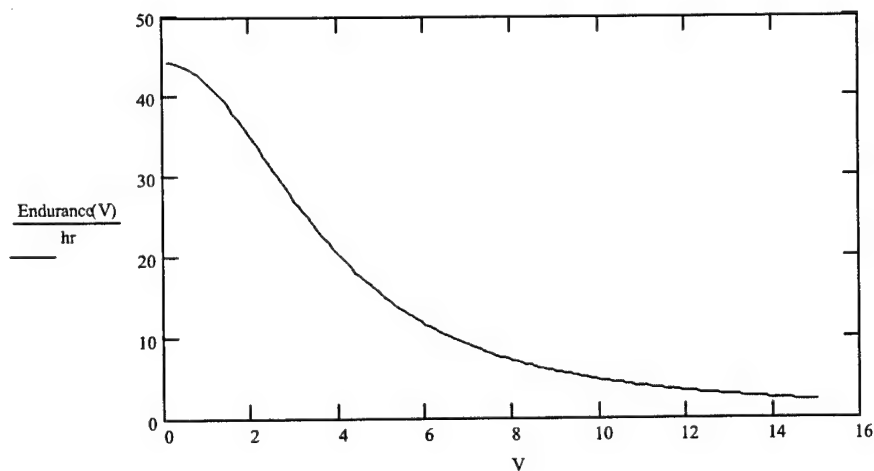
Endurance as a function of speed:

$$\text{Endurance}(V) := \frac{E_{\text{Installed}}}{BP(V) + P_{\text{HotelReq}}}$$

V1 =

4
6
8
10

Endurance (V1) =	
20.266	hr
11.566	
7.082	
4.663	



Endurance based on mission profile:

System endurance requirement:

$$T_{\text{endurance\_req}} = 7.768 \text{ hr}$$

Time margin (incorporates adjustment from System Model to set all vehicle endurances equal):

$$T_{\text{margin}} := T_{\text{endurance\_req}} - (T_{\text{transit}} + T_{\text{search}} + T_{\text{excursion}} + T_{\text{prosecute}}) \quad T_{\text{margin}} = 2.767 \text{ hr}$$

Energy consumption:

$$E_{\text{transit}} := BP \left( \frac{V_{\text{transit}}}{\text{knt}} \right) \cdot T_{\text{transit}} \quad E_{\text{transit}} = 1.094 \text{ kW}\cdot\text{hr}$$

$$E_{\text{search}} := BP \left( \frac{V_{\text{search}}}{\text{knt}} \right) \cdot T_{\text{search}} \quad E_{\text{search}} = 2.313 \text{ kW}\cdot\text{hr}$$

$$E_{\text{excursion}} := BP \left( \frac{0.5 V_{\text{search}}}{\text{knt}} \right) \cdot T_{\text{excursion}} \quad E_{\text{excursion}} = 0.081 \text{ kW}\cdot\text{hr} \quad \text{Assumes } 1/2 V_{\text{search}} \text{ during excursions}$$

$$E_{\text{prosecute}} := BP \left( \frac{V_{\text{prosecute}}}{\text{knt}} \right) \cdot T_{\text{prosecute}} \quad E_{\text{prosecute}} = 0 \text{ kW}\cdot\text{hr} \quad \text{Assumes } V_{\text{search}} \text{ during prosecutions}$$

$$E_{\text{margin}} := BP \left( \frac{V_{\text{search}}}{\text{knt}} \right) \cdot T_{\text{margin}} \quad E_{\text{margin}} = 1.68 \text{ kW}\cdot\text{hr} \quad \text{Assumes margin time spent at } V_{\text{search}}$$

$$E_{\text{Propulsion\_total}} := E_{\text{transit}} + E_{\text{search}} + E_{\text{excursion}} + E_{\text{prosecute}} + E_{\text{margin}} \quad E_{\text{Propulsion\_total}} = 5.168 \text{ kW}\cdot\text{hr}$$

$$E_{\text{Mission}} := E_{\text{Propulsion\_total}} + E_{\text{HotelReq}}$$

$$E_{\text{Mission}} = 6.833 \text{ kW}\cdot\text{hr}$$

Compare to:  $E_{\text{Mission\_est}} = 5.98 \text{ kW}\cdot\text{hr}$

$$E_{\text{Surplus}} := E_{\text{Installed}} - E_{\text{Mission}}$$

$$E_{\text{Surplus}} = 2.667 \text{ kW}\cdot\text{hr}$$

$$E_{\text{Energy}} := \frac{E_{\text{Surplus}}}{E_{\text{Mission}}}$$

Balance energy error to +/- 1%.

$$E_{\text{Energy}} = 0.39$$

## VI. OUTPUT TO EFFECTIVENESS MODEL

$$L = 10.5 \text{ ft}$$

$$D = 21 \text{ m}$$

# Appendix C

## Effectiveness Model

### MCM EFFECTIVENESS MODEL

#### Model Description

Include place for description of mission

#### INPUTS

Directions:

IMPORTANT: Output files are written at the end of this file. If a new file is being created using a file for another system, be sure to change the output file names FIRST so as to avoid writing over the output for the other file.

1. Insert links for System Model file and each AUV Design Module file (one for each vehicle type); delete old link first and then re-insert reference link (Insert\Reference\... use relative link option).
2. For each vehicle link, make sure the L & D lines are inserted and the correct subscripts are used.
3. When any changes are made to other files, these links must be updated by clicking once on the link and pressing F9. Do this for each link. (Be sure link files are saved first.)


System Model Link:

 Reference: C:\My Documents\MIT\Thesis\Modeling\Master\System Model - Master.mcd(R)

$$n_{veh\_total} := \text{if} \left( \text{numtype} > 1, \sum \text{numveh}, \text{numveh} \right) \quad n_{veh\_total} = 3$$

Vehicle Links (one for each type):

 numtype = 2

 Reference: C:\My Documents\MIT\Thesis\Modeling\Master\AUV Design Module - Master.mcd(R)

$$LL_1 := L \quad LL_1 = 10.5 \text{ ft} \quad DD_1 := D \quad DD_1 = 21 \text{ in}$$

 Reference: C:\My Documents\MIT\Thesis\Modeling\Case One\S2 AUV2.mcd(R)

$$LL_2 := L \quad LL_2 = 8 \text{ ft} \quad DD_2 := D \quad DD_2 = 12 \text{ in}$$

Add additional links for each AUV type

## **MOE-MOP HIERARCHY**

**Blue = MOE   Purple = Sub-MOE   Black = MOP**

<b>Mission Time</b>	<b>Effective Area Coverage Rate</b>	<i>Multiple system parameters (modeled)</i>
<b>Mission Accomplishment</b>	<b>Search Level (through identification)</b>	<i>Multiple system parameters (modeled)</i>
	<b>Localization Accuracy</b>	Navigation accuracy (modeled)
	<b>Clearance Level</b>	<i>Multiple system parameters (modeled)</i>
<b>Autonomy</b>	<b>Lift Support</b>	System Footprint (modeled)
	<b>Host Support</b>	Host Platform Requirement(utility fcn)
<b>Communication</b>	<b>Reporting Frequency</b>	Reporting Frequency (utility fcn)
	<b>Data Type</b>	Data Type (utility fcn)
<b>Coverttness</b>	<b>Deployment Phase</b>	Platform Type (utility fcn)
	<b>Mission Phase</b>	Platform Type and Location (utility fcn)
	<b>Recovery Phase</b>	Platform Type (utility fcn)

## MOE WEIGHTS

This method for establishing the MOE weights is based on an Analytical Hierarchy Process technique sometimes called the "pairwise comparison matrix method". Here, only the upper-level MOE weights are derived using the matrix method; the sub-MOE are assigned directly because there are no more than three in any group to compare. To obtain valid weights, a formal survey process should be undertaken to extract the warfighter's preferences. Each pair combination  $[n(n-1)/2]$ , where  $n$  is the number of MOE] should be included in the assessment.

A simplified approach taken for this thesis is shown here. The number pairwise comparisons is kept to the minimum  $[n-1]$ , and all values are assigned by the author.

Instructions:

1. Place MOE in order from most important to least important.
2. Re-order and update indices.
3. Enter comparison values for the four  $R_{ij}$

### MOE Order

1 Time	Set indices:	Time	$tm := 1$
2 Accomplishment		Mission Accomplishment	$ma := 2$
3 Communication		Communication	$co := 3$
4 Autonomy		Autonomy	$au := 4$
5 Covertress		Covertress	$cv := 5$

### MOE Pairwise Comparisons

Time vs Accomplishment	$RI_{12} := 1.5$	Read $R_{ij}$ as "relative importance of $i$ over $j$ "
Time vs Communication	$RI_{13} := 4$	
Time vs Autonomy	$RI_{14} := 6$	
Time vs Covertress	$RI_{15} := 8$	
Accomplishment vs Communication	$RI_{23} := \frac{RI_{13}}{RI_{12}}$	$RI_{23} = 2.667$
Accomplishment vs Autonomy	$RI_{24} := \frac{RI_{14}}{RI_{12}}$	$RI_{24} = 4$
Accomplishment vs Covertress	$RI_{25} := \frac{RI_{15}}{RI_{12}}$	$RI_{25} = 5.333$
Communication vs Autonomy	$RI_{34} := \frac{RI_{14}}{RI_{13}}$	$RI_{34} = 1.5$
Communication vs Covertress	$RI_{35} := \frac{RI_{15}}{RI_{13}}$	$RI_{35} = 2$
Autonomy vs Covertress	$RI_{45} := \frac{RI_{15}}{RI_{14}}$	$RI_{45} = 1.333$

## MOE Pairwise Comparison Matrix and Eigenvalue Problem

$$\text{MOE} := \begin{pmatrix} 1 & \text{RI}_{12} & \text{RI}_{13} & \text{RI}_{14} & \text{RI}_{15} \\ \text{RI}_{12}^{-1} & 1 & \text{RI}_{23} & \text{RI}_{24} & \text{RI}_{25} \\ \text{RI}_{13}^{-1} & \text{RI}_{23}^{-1} & 1 & \text{RI}_{34} & \text{RI}_{35} \\ \text{RI}_{14}^{-1} & \text{RI}_{24}^{-1} & \text{RI}_{34}^{-1} & 1 & \text{RI}_{45} \\ \text{RI}_{15}^{-1} & \text{RI}_{25}^{-1} & \text{RI}_{35}^{-1} & \text{RI}_{45}^{-1} & 1 \end{pmatrix} \quad \text{MOE} = \begin{pmatrix} 1 & 1.5 & 4 & 6 & 8 \\ 0.667 & 1 & 2.667 & 4 & 5.333 \\ 0.25 & 0.375 & 1 & 1.5 & 2 \\ 0.167 & 0.25 & 0.667 & 1 & 1.333 \\ 0.125 & 0.188 & 0.5 & 0.75 & 1 \end{pmatrix}$$

$$\text{eigenvals}(\text{MOE}) = \begin{pmatrix} 0 \\ 5 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\text{max\_ev} := \max(\text{eigenvals}(\text{MOE}))$$

$$\text{max\_ev} = 5$$

Inconsistency ratio  
(must be less than 0.01)

$$\text{IR} := \frac{\text{Re}(\text{max\_ev}) - \text{rows}(\text{eigenvals}(\text{MOE}))}{\text{rows}(\text{eigenvals}(\text{MOE}))}$$

$$\text{IR} = 0$$

Weights obtained from eigenvector associated with maximum eigenvalue:

$$\text{eigenv}(\text{MOE}, \text{Re}(\text{max\_ev})) = \begin{pmatrix} 0.803 \\ 0.535 \\ 0.201 \\ 0.134 \\ 0.1 \end{pmatrix}$$

$$\text{sum\_ev} := \sum \text{eigenv}(\text{MOE}, \text{Re}(\text{max\_ev})) \quad \text{sum\_ev} = 1.774$$

Normalized MOE weights:

$$\text{MOE\_wt} := \frac{\text{eigenv}(\text{MOE}, \text{Re}(\text{max\_ev}))}{\text{sum\_ev}}$$

$$\text{MOE\_wt} = \begin{pmatrix} 0.453 \\ 0.302 \\ 0.113 \\ 0.075 \\ 0.057 \end{pmatrix}$$

Checksum:

$$\sum \text{MOE\_wt} = 1$$

## TIME MOE

### MOE Description

The **Time MOE** represents the time required for the AUV system to accomplish the assigned mission objectives.

### Sub-MOE Description(s)

**Effective Area Coverage Rate** Ratio of the total search area to the total amount of time required to complete the mission objective(s), from AUV system deployment to recovery. Includes time spent in the search area plus transit time to/from the search area.

Alternate:

**Total Mission Time** The total amount of time from AUV system deployment to recovery. Includes time spent in the search area plus transit time to/from the search.

### Weights

**Time MOE**

$Wt_{TIME} := MOE_{wt_{tm}}$

$Wt_{TIME} = 0.453$

**Area Coverage Rate**

$Wt_{ACR} := 1.0$

$Wt_{ACR} = 1$

### Contributing System Parameters (MOP)

Number of tracks	$N = 7$	Total track run distance	$d_{track\_runs} = 21 \text{ nm}$
Track spacing	$D_{track} = 571.429 \text{ yd}$	Total turn distance	$d_{turns} = 1.862 \text{ nm}$
Runs per track	$J = 1$	Distance into search area	$d_{ingress} = 1 \text{ nm}$
Track length	$L_{searcharea} = 3 \text{ nm}$	Distance out of search area	$d_{egress} = 5 \text{ nm}$
Search speed	$V_{search} = 10.125 \text{ ft sec}^{-1}$	Distance to recharge point	$d_{recharge}$
Transit speed	$V_{transit} = 10 \text{ kt}$	Number of recharges	$N_{recharge}$
		Recharge time	$T_{recharge}$

### Contributing Mission Parameters

Search area dimensions	$L_{searcharea} = 3 \text{ nm}$
	$W_{searcharea} = 4 \times 10^3 \text{ yd}$
Estimated number of mines	$NM = 25$

## Relationships

MOE Determination Method:    **MODELING**

$$T_{\text{mission}} = T_{\text{search}} + T_{\text{transit}} + T_{\text{service}} + T_{\text{excursion}} = T_{\text{endurance\_req}}$$

$$ACR_{\text{eff}} = \frac{L_{\text{searcharea}} W_{\text{searcharea}}}{T_{\text{mission}}}$$

## Results

$$T_{\text{mission}} := T_{\text{endurance\_req}}$$

$$T_{\text{mission}} = 7.658 \text{ hr}$$

$$ACR_{\text{eff}} := \frac{L_{\text{searcharea}} W_{\text{searcharea}}}{T_{\text{mission}}}$$

$$ACR_{\text{eff}} = 0.774 \frac{\text{nm}^2}{\text{hr}}$$

## MISSION ACCOMPLISHMENT MOE

### MOE Description

The **Mission Accomplishment MOE** represents the estimated condition of the searched/cleared area after the mission is completed. This MOE reveals the extent to which any specified mission objectives were achieved or surpassed.

### Sub-MOE Description(s)

<b>Search Level (through identification)</b>	FOR NON-CLEARANCE MISSIONS ONLY. Cumulative joint probability of detecting, classifying, and correctly identifying mines within the specified search area. Also known as "Percent Search".
<b>Localization Accuracy</b>	FOR NON-CLEARANCE MISSIONS ONLY. Represents the distance error between the reported mine positions and the actual mine positions. Also called "contact position error". For this model, the contact position error is taken as a function of the system navigation error (%DT). [Note: if determined by post-analysis or simulation, localization error could be given as Distance Root Mean Squared (DRMS).]
<b>Clearance Level</b>	FOR CLEARANCE MISSIONS ONLY. Cumulative joint probability of detecting, classifying, identifying (optional), and neutralizing mines within the specified search area. Also known as "Percent Clearance". <i>Note: Model is currently unable to handle clearance missions.</i>



## Weights

<b>Mission Accomplishment MOE</b>	$Wt_{ACMP} := MOE\_wt_{ma}$	$Wt_{ACMP} = 0.302$	
<b>Search Level (through ID)</b>	Enter value: $Wt_{SL} := 0.6$	$Wt_{SL} = 0.6$	
<b>Localization Accuracy</b>	$Wt_{LA} := 1 - Wt_{SL}$	$Wt_{LA} = 0.4$	
<b>Clearance Level</b>	$Wt_{CL} := \text{if}(Wt_{SL} = 0, 1, 0)$	$Wt_{CL} = 1$	Disabled

## Contributing System Parameters (MOP)

Number of tracks	$N = 7$
Runs per track	$J = 1$
Track spacing	$D_{track} = 571.429\text{yd}$
Standard deviation of track keeping	$\sigma = \begin{pmatrix} 15 & 30 & 0 & 0 \\ 15 & 30 & 0 & 0 \\ 15 & 30 & 0 & 0 \end{pmatrix} \text{ft}$
Characteristic search width	$A = \begin{pmatrix} 588 & 588 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \text{yd}$
Characteristic probability of detection/classification	$B = \begin{pmatrix} 0.876 & 0.9 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$
Maximum acceptable position error	$\text{max\_pos\_error} = 30\text{yd}$
System Navigation Error (%DT)	$\%DT = 0.05$

## Contributing Mission Parameters

Target strength	$\gamma = -30\text{dB}$
Bottom type	$BT = 4$
Water depth	$d_{avg} = 400\text{ft}$

## Relationships

MOE Determination Method: **MODELING**

$$P_{\text{search}} = (1 - \mu) \cdot P_{\text{imm}} \cdot (1 - e^{-M \cdot Y})$$

Note: Percent clearance just adds probability of neutralization

$$P_{\text{clear}} = (1 - \mu) \cdot P_{\text{imm}} \cdot P_{\text{nm}} \cdot (1 - e^{-M \cdot Y})$$

where  $M = \frac{J \cdot A \cdot B}{D_{\text{track}}}$

$$Y = \frac{2 \cdot \sigma}{A \cdot B} \int_0^{\infty} \ln \left[ 1 - B \cdot \left( \text{cnorm} \left( u + \frac{A}{2 \cdot \sigma} \right) - \text{cnorm} \left( u - \frac{A}{2 \cdot \sigma} \right) \right) \right] du$$

$$\text{avg\_pos\_error} = 0.5 \cdot \text{max\_pos\_error}$$

## Results

$$P_{\text{search}} := P_{\text{search}}$$

$$P_{\text{search}} = 0.977$$

$$\text{avg\_pos\_error} := .5 \cdot \text{max\_pos\_error}$$

$$\text{avg\_pos\_error} = 15 \text{yd}$$

## AUTONOMY MOE

### MOE Description

The **Autonomy MOE** represents the independence of the system from logistics support and/or oversight for guidance and tasking. It is expressed in terms of a normalized score on a scale of 0 to 1.

### Sub-MOE Description(s)

#### Lift Support

Amount of cargo space required for deployment/recovery of the system, given in terms of area (e.g. sqft)

#### Host Support

Level of service and/or command and control support required during a mission. This requirement is specified in terms of discrete host responsibility alternatives (e.g. dedicated platform, remote command and control, none, etc.)

### Weights

#### Autonomy MOE

$$Wt_{\text{ATMY}} := \text{MOE\_wt}_{\text{au}}$$

$$Wt_{\text{ATMY}} = 0.075$$

#### Lift Support

Enter value:  $Wt_{\text{LR}} := 0.25$

$$Wt_{\text{LR}} = 0.25$$

#### Host Support

$$Wt_{\text{HR}} := 1 - Wt_{\text{LR}}$$

$$Wt_{\text{HR}} = 0.75$$

## Contributing System Parameters (MOP)

Number of vehicle types	numtype = 2
Number of vehicles (each type)	numveh = (1 2)
Vehicle(s) dimensions	LL = $\begin{pmatrix} 10.5 \\ 8 \end{pmatrix}$ ft      DD = $\begin{pmatrix} 21 \\ 12 \end{pmatrix}$ in
Reliability/redundancy	reliability = "LOW"
Recharge method	recharge = "NR"
Host-system communication method	comm_method = "RF-SAT"

## Relationships

### MOE Determination Method    MODELING / UTILITY FUNCTION

Lift Support = Total System Footprint

$$FP_{sys} = \sum_{i=1}^{numtype} f_{stow_i} \cdot numveh_i \cdot FP_{veh_i} \quad \text{where} \quad FP_{veh_i} = L_i \cdot D_i \quad [sqft]$$

$f_{stow}$  is stowage multiplier

Host Support

None required	1.0
Command/control only (remote)	0.7
In-theater/dedicated	0.0

## Results

L := LL      D := DD

$$FP_{sys} := \text{if} \left( numtype > 1, \sum_{i=1}^{numtype} numveh_{1,i} \cdot L_1 \cdot D_1, numveh \cdot L_1 \cdot D_1 \right)$$

$$FP_{sys} = 55.125 \text{ ft}^2$$

Note: Footprint calculation does not include any system/vehicle stowage factors

$$Score_{host} := \begin{cases} 0 & \text{if (reliability = "LOW" } \vee \text{ comm\_method = "AM" } \vee \text{ comm\_method = "RF-LOS" } \vee \text{ recharge = "HOST") } \\ 0.7 & \text{if comm\_method = "RF-SAT" } \\ 1.0 & \text{otherwise} \end{cases}$$

$$Score_{host} = 0.7$$

## COMMUNICATION MOE

### MOE Description

The **Communication MOE** represents the system's capability to receive and/or transmit information from/to a host. It is expressed in terms of a normalized score on a scale of 0 to 1.

### Sub-MOE Description(s)

<b>Reporting Frequency</b>	Frequency of transmissions from system to host or vice versa
<b>Data Type</b>	Low: CAD/CAC, system position/status, contact positions, etc. Also, command and control-related information from host; High: Post-processed data intended for human interpretation (e.g sonar imagery or "snippets")

### Weights

<b>Communication MOE</b>	$Wt_{COMM} := MOE_{wt_{co}}$	$Wt_{COMM} = 0.113$
<b>Reporting Frequency</b>	Enter value: $Wt_{RF} := 0.3$	$Wt_{RF} = 0.3$
<b>Data Type</b>	$Wt_{DT} := 1 - Wt_{RF}$	$Wt_{DT} = 0.7$

### Contributing System Parameters

Host-system communication method	comm_method = "RF-SAT"
Reporting frequency	report_freq = "PRD"

### Relationships

Data Type (Content)	Reporting Frequency
High Content 1.0	Continuous 1.0
Low Content 0.7	Periodic 0.5
None 0.0	None 0.0

### Results

$$Score_{data\_type} := \begin{cases} 0 & \text{if comm\_method} = \text{"NR"} \\ 0.7 & \text{if comm\_method} = \text{"AM"} \\ 1.0 & \text{otherwise} \end{cases}$$

$$Score_{data\_type} = 1$$

$$Score_{report\_freq} := \begin{cases} 0 & \text{if report\_freq} = \text{"NR"} \\ 0.7 & \text{if report\_freq} = \text{"PRD"} \\ 1.0 & \text{otherwise} \end{cases}$$

$$Score_{report\_freq} = 0.7$$

## COVERTNESS MOE

### MOE Description

The **Covertness MOE** represents the extent to which the system's presence and efforts are difficult to detect. It is expressed in terms of a normalized score on a scale of 0 to 1.

### Sub-MOE Description(s)

<b>Deployment Phase</b>	Ability to avoid detection during deployment phase of operation.
<b>Mission Phase</b>	Ability to avoid detection during mission (search/clearance) phase of operation.
<b>Recovery Phase</b>	Ability to avoid detection during recovery phase of operation.

### Weights

<b>Covertness MOE</b>	$Wt_{CVRT} := MOE\_wt_{cv}$	$Wt_{CVRT} = 0.057$
<b>Deployment Phase</b>	Enter value: $Wt_{DP} := 0.4$	$Wt_{DP} = 0.4$
<b>Mission Phase</b>	Enter value: $Wt_{MP} := 0.25$	$Wt_{MP} = 0.25$
<b>Recovery Phase</b>	Enter value: $Wt_{RP} := 0.35$	$Wt_{RP} = 0.35$
Check sum: $Chk := \text{if}[(Wt_{DP} + Wt_{MP} + Wt_{RP}) = 1, "OK", "Weights must sum to 1.0"]$		

### Contributing System Parameters

Clandestine delivery method	$cland\_deliv = "AIR"$
Clandestine recovery method	$cland\_recov = "SURF"$
Host requirement (from Autonomy MOE)	

### Relationships

Deployment Platform Type		Recovery Platform Type		Mission Phase Platform Type & Location	
None Req'd	1.0	None Req'd	1.0	None Req'd	1.0
Sub	0.9	Sub	0.9	Satellite/air link	0.9
Air	0.3	Air	0.3	Sub	0.6
Surf	0.0	Surf	0.0	Surf	0.0

**Results**

$x := \text{cland\_deliv} \quad x = \text{"AIR"}$

$$\text{Score}_{\text{deploy}} := \begin{cases} 0 & \text{if } x = \text{"SURF"} \\ 0.3 & \text{if } x = \text{"AIR"} \\ 0.9 & \text{if } x = \text{"SUB"} \\ 1.0 & \text{otherwise} \end{cases}$$

$$\text{Score}_{\text{deploy}} = 0.3$$

$y := \text{cland\_recoy} = \text{"SURF"}$

$$\text{Score}_{\text{recoy}} := \begin{cases} 0 & \text{if } y = \text{"SURF"} \\ 0.3 & \text{if } y = \text{"AIR"} \\ 0.9 & \text{if } y = \text{"SUB"} \\ 1.0 & \text{otherwise} \end{cases}$$

$$\text{Score}_{\text{recoy}} = 0$$

$z := \text{Score}_{\text{host}} \quad z = 0.7$

$$\text{Score}_{\text{mission}} := \begin{cases} 1.0 & \text{if } z = 1 \\ 0.9 & \text{if } z \neq 0 \wedge z \neq 1 \\ \text{otherwise} & \\ & \begin{cases} 0.6 & \text{if } x = \text{"SUB"} \\ 0 & \text{otherwise} \end{cases} \end{cases}$$

$$\text{Score}_{\text{mission}} = 0.9$$

Note: assumes sub will serve as mission host if sub is the delivery platform

## SUMMARY

### MOE Values:

$$T_{\text{mission}} = 7.658 \text{ hr}$$

$$ACR_{\text{eff}} = 0.774 \frac{\text{nm}^2}{\text{hr}}$$

$$P_{\text{search}} = 0.977$$

$$\text{avg\_pos\_error} = 15 \text{ yd}$$

$$FP_{\text{sys}} = 55.125 \text{ ft}^2$$

$$\text{Score}_{\text{host}} = 0.7$$

$$\text{Score}_{\text{report\_freq}} = 0.7$$

$$\text{Score}_{\text{data\_type}} = 1$$

$$\text{Score}_{\text{deploy}} = 0.3$$

$$\text{Score}_{\text{recov}} = 0$$

$$\text{Score}_{\text{mission}} = 0.9$$

MOEResults :=

$$\left( \begin{array}{c} \frac{T_{\text{mission}}}{\text{hr}} \\ \frac{ACR_{\text{eff}}}{\text{nm}^2 \cdot \text{hr}^{-1}} \\ P_{\text{search}} \\ \frac{\text{avg\_pos\_error}}{\text{yd}} \\ \frac{FP_{\text{sys}}}{\text{ft}^2} \\ \text{Score}_{\text{host}} \\ \text{Score}_{\text{report\_freq}} \\ \text{Score}_{\text{data\_type}} \\ \text{Score}_{\text{deploy}} \\ \text{Score}_{\text{recov}} \\ \text{Score}_{\text{mission}} \end{array} \right)$$

Output link  
not shown

### MOE Weights:

$$Wt_{\text{TIME}} = 0.453$$

$$Wt_{\text{ACR}} = 1$$

$$Wt_{\text{ACMP}} = 0.302$$

$$Wt_{\text{SL}} = 0.6$$

$$Wt_{\text{LA}} = 0.4$$

$$Wt_{\text{ATMY}} = 0.075$$

$$Wt_{\text{LR}} = 0.25$$

$$Wt_{\text{HR}} = 0.75$$

$$Wt_{\text{COMM}} = 0.113$$

$$Wt_{\text{RF}} = 0.3$$

$$Wt_{\text{DT}} = 0.7$$

$$Wt_{\text{CVRT}} = 0.057$$

$$Wt_{\text{DP}} = 0.4$$

$$Wt_{\text{MP}} = 0.25$$

$$Wt_{\text{RP}} = 0.35$$

MOEWeights :=

$$\left( \begin{array}{c} Wt_{\text{TIME}} \\ Wt_{\text{ACMP}} \\ Wt_{\text{ATMY}} \\ Wt_{\text{COMM}} \\ Wt_{\text{CVRT}} \end{array} \right)$$

Output link  
not shown

SUBMOEWeights :=

$$\left( \begin{array}{c} Wt_{\text{ACR}} \\ Wt_{\text{SL}} \\ Wt_{\text{LA}} \\ Wt_{\text{LR}} \\ Wt_{\text{HR}} \\ Wt_{\text{RF}} \\ Wt_{\text{DT}} \\ Wt_{\text{DP}} \\ Wt_{\text{MP}} \\ Wt_{\text{RP}} \end{array} \right)$$

Output link  
not shown

### AUV MCM System OMOE Spreadsheet

**System name:** S1 - Single Vehicle, Multiple Sensors

RED = pre-defined weights  
**Capability**

BLUE = calcs.  
**MOP**

MAGENTA = Model Score  
**MOP**  
**Goal**      **Attained**

			Threshold		
0.453	Mission Time	0.217	1.000	Eff Area Cov Rate	0.217
			0.2	1.5	0.482
			0.600	Search Level	0.612
			0.94	1	0.977
0.302	Mission Accomplishment	0.678	0.400	Localization Accuracy	0.778
			50	5	15
			0.000	Clearance Level	1.000
			1	0	0
			1.000	Check = 1.000	
Overall MOE		0.432	0.250	Lift Support	1.000
	0.075	Autonomy	0.250		
			0.750	Host Support/Oversight	0.000
			Dedicated	None Req'd	0.00
			1.000	Check = 1.000	
			0.300	Reporting Frequency	0.700
0.113	Communication	0.910	None	Continuous	0.70
			0.700	Data Type	1.000
			None	High	1.00
			1.000	Check = 1.000	
			0.400	Deploy Phase	0.300
			Surf	None Req'd	0.30
0.057	Covertiness	0.120	0.250	Recovery Phase	0.000
			Surf	None Req'd	0.00
			0.350	Mission Phase	0.000
			Surf (ded)	None Req'd	0.00
			1.000	Check = 1.000	
			1.000	Check = 1.000	



## Appendix D

# AUV Sub-system Databases

The databases shown in this Appendix are accessed through the Excel link in the System Model. In general, they contain weight, volume, and electric power characteristics for a catalog of AUV sub-systems. In the interface sheet of the Excel link, the user configures each AUV by selecting the proper designation from among the options. The corresponding information is then extracted from the databases using lookup features and passed to the System Model (i.e. for the AUV Design Module). The items and numeric values in these databases should be observed with caution, as they were derived from various sources and have not been validated.

## SONARS DATABASE

Source: MCM Future Systems Study Workbook

Comments: ALS/SAS data for wide beam only (meant for deeper water, i.e. 200+ ft); wt/vol/pwr given for arrays and electronics, but not signal processing

Sonar Type	Sensor Desig	Min Vehicle Diameter in	Wt lbs	Vol cu in	Power w
Ahead Looking Sonars (ALS)	ALS-4	4.875	9.1	396	87.3
	ALS-7	7.5	10.6	475	91.6
	ALS-12	12.75	14.2	617	128.6
	ALS-21	21	20.3	924	139.4
	ALS-36	36	37.3	1726	142.7
	ALS-54	54	68.2	3160	174.2
Sythetic aperature sonars (SAS)	SAS-4	4.875	2.9	146	18.9
	SAS-7	7.5	4.3	284	26.6
	SAS-12	12.75	9.3	954	48
	SAS-21	21	19.6	2633	76.1
	SAS-36	36	53.3	11296	81.9
	SAS-54	54	127.3	33572	82.1
Side-scan sonars (SS)	SS-12	12	7.0	716	36.0
	SS-21	21	14.7	1975	57.1

Note: must change lookup formulas in SysDefn sheet if expanded past current point

## ID SENSORS DATABASE

Source: MCM Future System WG

Comments: Traditional sensors listed here; see WG paper for more advanced concepts

ID Sensor Type	Sensor Desig	Min Vehicle Diameter in	Wt lbs	Vol cu in	Power w	Diameter in	Length in
Deep Sea SS-126C Video/Lighting	ID-LOW	n/a	0.20	2.88	5	1.26	2.31
Benthos DSC 4000 Dig Still Camera	ID-MED	n/a	5.00	143.14	12	4.50	9.00
Benthos DSC 5010 Dig Still Camera	ID-HIGH	n/a	7.25	143.14	45	4.50	9.00

Note: can expand to cell 20 without changing current lookup formulas in SysDefn sheet

## NAVIGATION PACKAGE DEFINITION

Instructions for adding or modifying navigation packages:

1. Make entries in yellow section only. Gray sections are updated automatically.
2. To add a component to a nav package, highlight the second row of a package (inside the framed box only), and insert rows using the "shift cells down" option. Type the new component designation number in the 4th column.
3. To create an entirely new nav package, either replace an existing one or insert cells as described in item 2 (except highlight the white between the frames instead).

Nav Suite	Accuracy %DT	Vehicle Type(s)	Component Designations	Component Names	Weight (lbs)	Volume (cu in)	Power (W)
INS	Rsvd for future	Hunter	14	Ring laser gyro	1.0	16.5	1.6
			18	Pendulous	0.8	4.4	0.2
			INS	Subtotal	1.8	20.9	1.8
INS-DVS	Rsvd for future	Guide	14	Ring laser gyro	1.0	16.5	1.6
			18	Pendulous	0.8	4.4	0.2
		Hunter	2	DVS	8.0	118.8	20.0
			INS-DVS	Subtotal	9.8	139.7	21.8
DR-DVS-GPS	Rsvd for future	Guide	5	Gyrocompass	8.0	198.9	4.0
			2	DVS	8.0	118.8	20.0
			27	Military Rcvr	0.2	6.8	1.2
			DR-DVS-GPS	Subtotal	16.2	324.5	25.2
INS-ABR	Rsvd for future	Hunter	14	Ring laser gyro	1.0	16.5	1.6
			18	Pendulous	0.8	4.4	0.2
			24	Super-directional	4.6	402.1	0.3
			INS-ABR	Subtotal	6.4	423.0	2.0
DR-DVS-ABR	Rsvd for future	Hunter	5	Gyrocompass	8.0	198.9	4.0
			2	DVS	8.0	118.8	20.0
			24	Super-directional	4.6	402.1	0.3
			DR-DVS-ABR	Subtotal	20.6	719.8	24.3
INS-DVS-GPS	Rsvd for future	Guide	14	Ring laser gyro	1.0	16.5	1.6
			18	Pendulous	0.8	4.4	0.2
			2	DVS	8.0	118.8	20.0
			27	Military Rcvr	0.2	6.8	1.2
			INS-DVS-GPS	Subtotal	10.0	146.5	23.0

## NAVIGATION COMPONENTS DATABASE

Source: MCM Future Systems Study Workbook  
Comments:

Navigation Technique	System/Component Type	Desig	Item	Model	Length (in)	Length Dim	Width (in)	Width Dim	Height (in)	Volume(cu in)
Dead Reckoning	Velocity Sensors	1	EM LOG	AGILOG	8.0	dia	8.0	dia	11.4	573.0
		2	DVS	microDVL	5.5	dia	5.5	dia	5.0	118.8
		3	Correlation	ACCP	17.3	--	17.3	--	8.7	2603.8
		4	Compass	C100	4.5	--	1.8	--	1.1	8.9
	Heading Sensors	5	Gyrocompass	GyroTrac	7.8	--	5.0	--	5.1	198.9
		6	North-finding gyro	MiniFOG	11.8	dia	11.8	dia	16.0	1749.7
		7	Altimeter	PSA-900	4.0	dia	4.0	dia	11.5	144.5
		8	Depth Sounder	TJE	1.5	dia	1.5	dia	2.0	3.5
	Roll/pitch Sensor	9	Clinometer	AccuStar	2.5	dia	2.5	dia	1.2	5.9
		10	Inclinometer	TCM2	2.5	--	2.0	--	1.3	6.3
	Sound Speed Sensor	11	CTD	MicroSVP	2.9	dia	2.9	dia	13.8	93.7
		12	Velocimeter	Smart Sensor	1.8	dia	1.8	dia	12.4	31.6
Inertial Navigation	Gyroscopes	13	Mechanical	RG78	3.7	dia	2.0	dia	1.8	19.0
		14	Ring laser gyro	GG1320	3.5	dia	3.5	dia	1.8	16.5
		15	Fiber optic	Ecore 100	4.3	--	3.5	--	1.6	24.1
		16	MEMS	Gyrochip QRS11	1.5	dia	1.5	dia	0.6	1.1
		17	Mass-spring	LA67	1.0	dia	1.0	dia	2.5	2.0
	Accelerometers	18	Pendulous	LSBC	2.6	--	1.2	--	1.4	4.4
		19	MEMS	CXL02F3	2.0	--	1.2	--	0.9	2.1
		20	IMU 1	TGAC-RC	7.9	--	8.7	--	13.8	939.2
	IMU	21	IMU 2	LN-200	3.5	dia	3.5	dia	3.4	32.2
		22	IMU 3	Motion PAK	3.0	--	3.0	--	3.6	32.4
Acoustic Baseline	Long Baseline (LBL)	23	Omni-directional	Trackpoint II	2.8	dia	2.8	dia	24.0	142.5
		24	Super-directional	Type 7978	7.2	dia	7.2	dia	39.5	1608.2
Radio Navigation	GPS	25	Civilian Rcvr	Sensor II	4.2	--	2.3	--	0.6	5.7
		26	DGPS Rcvr	DSM212L	7.7	--	5.7	--	2.0	87.8
	GLONASS	27	Military Rcvr	12 MPE-1	4.2	--	2.7	--	0.6	6.8
		28	Receiver	GG24	6.5	--	4.0	--	0.6	15.6

## COMMUNICATIONS DATABASE

Source: None

Comments: Rough guesses only -- need to build database

	Desig	Wt lbs	Vol cu in	Power w
Acoustic Modems	AM	1.5	37.03	9
Laser Modems	LM	Future	Future	Future
RF Units	RF	1	24.69	3
Combinations	AM+RF	2.5	61.71	12.00

## COMPUTER/PROCESSOR DATABASE

Source: MCM Future System WG

Comments: Traditional sensors listed here; see WG paper for more advanced concepts

Computer/Processor Type	Desig	Wt lbs	Vol cu in	Power w
Basic Guidance, & Control & Veh Housekeeping	GC	2	75.00	15
Basic G&C + Kalman Filter	GC+K	3	100.00	20
Basic G&C + Kalman Filter + Sonar Post-Processor	GC+K+S	4	300.00	40

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